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HUMAN FACTORS IN WORK, MACHINE CONTROL AND EQUIPMENT DESIGN

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ANATOMICAL AND PHYSIOLOGICAL PRINCIPLES IN CHAIR AND TABLE DESIGN*

By W. F. Floyd

Department of Physiology, The Middlesex Hospital Medical School, London

and D. F. Roberts

Department of Human Anatomy, Oxford

General principles derived from anatomical, physiological and clinical studies of movement and posture may be applied to the design of furniture. The paper is concerned with this problem in relation to dimensions and shape of chairs and tables for office and general domestic use. From a study of the literature and consideration of the authors' own investigations the following conclusions emerge:

1. In sitting, changes of posture are important. A good chair should permit this.
2. In sitting, the weight of the trunk should be borne mainly by the ischial tuberosities. This probably maximises comfort. The thighs are anatomically and physiologically unsuited for supporting the body weight.
3. Therefore, the height of a chair seat should be no more than the length of the lower leg of the shortest person who will use the chair. There is however some conflict between the need for a seat height low enough to accommodate shorter persons and the need to avoid too great hip flexion, and the lumbar convexity which accompanies it, in the taller person sitting on a low seat. More than one seat height may be required to cover the range from the tallest male to the shortest female.
4. The maximum seat depth for comfort is determined by the length of the thighs of the shorter persons using the seat. Seat width is adequately measured by trochanteric width.
5. A substantially plane seat is preferable to one shaped or moulded to fit the backside. A backward slope of up to 5° may be suitable for some purposes.
6. The mechanics of rising from a seat require that no horizontal struts or other obstructions be placed between the front legs of a chair.
7. Trunk muscle activity in sitting is diminished by the use of a backrest, which should not however restrict the movement of the spinal column or of the arms. Support in the lumbar region within the limits of the 2nd to 5th lumbar vertebrae allows adequate free movement. A saddleshaped backrest like that recommended by Akerblom gives satisfactory support. Dimensions and angles of slope are considered in the paper.
8. Table and chair form a single anthropometric unit. Table height is closely correlated with elbow height. Elbows should be about the level of the working plane. The space between the under-surface of the table and the chair seat should be slightly greater than thigh thickness.

There is an awakening of interest in the scientific design of furniture. Many purchasers, no longer content to accept the traditional model, are questioning whether it is the most suitable for their particular requirements, and designers and manufacturers are of necessity echoing their enquiries. During the past few years we have received a steady stream of requests for assistance in problems of design and dimensions of various items of furniture, to which answers have been forthcoming either from further anthropometric and physiological investigations or by reference to published studies. A number of the latter covering several related biological fields are relevant to the design of chairs and tables. For example, studies of anatomical structure and function have given information as to where support for the body should or should not be provided. Clinical evidence demonstrates the results of insufficient attention to body mechanics. Studies of the times at which different muscle groups are brought into use and become fatigued in various activities, and the extent of muscle action in different body positions, indicate the relative physiological efficiency of working postures. During the past twenty years there have been many small-scale anthropometric surveys recording body measurements that have wide applicability to a variety of practical, industrial and military problems (see, for example, Le Gros Clark 1949, 1954, Roberts 1956). From such studies emerge general anatomical and physiological principles and anthropometric data which may be applied to the design of furniture. The present paper sets out those principles applicable to the dimensions, shape and general design of chairs and tables.

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* This paper is based on committee papers prepared by the authors for the British Standards Institution's Advisory Committee on Anthropometric Evidence for Equipment Dimensions, and British Standard B.S. 3044 : 1958.

§ 1. POSTURE

Ideas about good and bad posture are to be found in the literature at least as far back as Andry (1743), the father of orthopedics, who illustrated good and bad postures in his treatise "Orthopedia". Sitting upright he called a 'good posture'. Sitting in the position of full flexion he called a 'bad posture', the back he called 'crooked and round' and the posture 'ungraceful'. He was aware of deficiencies of posture arising from long-maintained bad postural habits, and he recommended functional treatment which amounted to the use of counteracting or antagonist muscles. There is much supporting evidence to be found in the clinical literature since his time. Long-maintained poor postural habits, arising for instance from the use of badly designed tools and furniture and methods of using them, frequently result in permanently implanted postural abnormalities, often accompanied by degenerative tissue changes and pain.

It is unlikely that there is one ideal sitting posture; several postures lie within an acceptable range because they are unlikely to lead to disabilities and pain, even if maintained for a long time. Bad postures may be conveniently defined as those which are known to cause or to be associated with disabilities or pain or other abnormalities. It is possible that some people are more prone to acquire these abnormalities.

Studies by Vernon (1922, 1924) on the fatiguability of muscles in relation to posture demonstrated that changes of posture delay the onset of muscular fatigue brought about by muscular work. These changes are effective when made either during the course of the work or during rest pauses. Electromyographic studies of the seated subject (Floyd, unpublished, Floyd and Silver 1951 a, b, 1955, Lundervold 1951 a, b, 1958, Silver, 1952) have shown that quite small changes in position, such as minor degrees of flexion or extension of the trunk or alteration of the angle of the knee when the foot is flat on the floor, can result in changes of activity in trunk and leg muscles such as, for example, the cessation of activity in the erectores spinae muscles of the back. Changes in posture can be extremely important therefore in relation to muscle activity and fatigue. For these reasons, in chair design there should be no question of attempting to hold the sitter in a particular posture. On this point, Akerblom (1948) commented succinctly: ". . . followed to its logical conclusion, a good chair is one which permits of as many good postures as possible being adopted without interference with the work" (p. 47). The dimensions and design of furniture should be such therefore as to accommodate the user satisfactorily without forcing him into poor and unnatural postures and should not discourage changes of posture.

It is important to consider not only the anatomically and physiologically normal person, i.e. a person without primary anatomical or physiological defects, but also those in whom the stresses induced by bodily activity at work and play and the effects of ageing have led to degenerative tissue changes and functional defects. The large number of individuals in this part of the normal range merges almost imperceptibly into those with low-grade diseases of posture, such as mild backache or sciatica. Problems of furniture design should therefore be examined not only from the point of view of the adolescent or the young athletic adult, but also from the point of view of the ageing adult and the substantial group of persons with low-grade postural disease which may make them more sensitive to long enforced postures, maldistribution of tissue pressure or prolonged static activity of muscle.

§ 2. SUPPORTING TRUNK WEIGHT

Experimental study of the distribution of pressure over a seat surface (Lay and Fisher 1940) suggests that comfort is at a maximum when the weight of the trunk is borne mainly by the ischial tuberosities. From the anatomical point of view, the region surrounding the tuberosities seems to be adapted to this end. The muscular tissue which covers these bony prominences in the standing individual is displaced laterally when the hip joint is flexed, so that in sitting the weight is sustained chiefly by the bony structures and not by the surrounding, more sensitive, softer tissues. The skin overlying the tuberosities is, after that of part of the feet and hands, "the best adapted to tolerate weight bearing" (Broman 1926). The corium of the buttocks is usually as thick as that of the sole of the foot, while the epidermis, although not as thick as that covering the sole and palm, is considerably thicker than that in most other regions of the body (Vierordt 1893).

According to Edwards and Duntley (1939) the blood supply of the skin over the tuberosities appears to be modified to withstand prolonged pressure. This opinion is supported by the contrast with what is found to happen when the pressure is distributed over the skin para-ischially. The skin overlying the soft tissues outside the ischial region, when compressed, becomes avascular due to expression of blood and occlusion of its blood supply. This is readily appreciated from the reactive hyperaemia which follows the release of pressure in this part. Distortion of the skin may also occur, and the soft tissues underlying this skin may become compressed.

Akerblom (1948, 1954) has shown clearly by means of radiographs that the soft tissues of the thigh are incapable of giving any support, and must undergo considerable compression, perhaps to a quarter of their full thickness, before the femur takes the weight; he commented that "owing to the extreme softness of the tissues it is not to be expected that any shaping of the seat, no matter how cleverly done, will make it into a good support for the thighs. Under almost all circumstances they will be compressed upwards as far as other factors . . . will allow". Such compression affects not only the muscles and their blood vessels, but also the nerves, especially the sciatic, with consequent discomfort and other undesirable effects on the soft tissues. Pressure on nerves and blood vessels may lead to numbness, tingling or anaesthesia. It may be concluded therefore that the thighs are anatomically and physiologically unsuited for supporting the weight of the sitting body.

§ 3. SEAT HEIGHT

The height of the seat should therefore be determined principally by the desirability of avoiding undue pressure on the soft tissues of the posterior aspect of the thigh. Accordingly, the front of a horizontal seat should be at most no higher than the length of the lower leg measured from the ground to the tendons of the flexors of the knees when the foot is flat on the floor and the knee is at a right angle. Anthropometric data on leg length relevant to the British population are given in Table 1. It can be calculated from the figures in the table that a seat height of 17 inches would accommodate 31 per cent of unshod men and 14 per cent of unshod women. If shoes are worn, these percentages become: 77 per cent of men, with 1-inch heel height, and 76 per cent of women, with $1\frac{3}{4}$-inch heel height. An 18-inch chair would satisfactorily accommodate only some 2 per cent of men and women without shoes, 31 per cent of men with a 1-inch heel and 38 per cent of women with a $1\frac{3}{4}$-inch heel.

Table 1

Dimensions of the Lower-leg Pertinent to a Choice of Seat Height

Sample	Sample number	Mean stature	Measurement	$\bar{x}$	σ
British male adults unshod	287	68·1	Floor to popliteal angle	16·6	0·8
,, ,, ,, unshod	58	68·2	*Floor to uppermost point on lateral tibial condyle	18·4	1·2
,, female adults shod	63	65·1	*Floor to lateral epicondyle of femur	20·0	1·1
,, ,, ,, unshod	63	63·3	*Floor to lateral epicondyle of femur	18·2	1·0

$\bar{x}$=mean ; σ=standard deviation ; all dimensions in inches.

* The last three items refer to bony points and hence require correction for the thickness of the soft tissues ; the estimated average height to the popliteal angle in the unshod women's sample is of the order of 15·9 inches.

The discomfort occasioned by seats so high that users are unable to place their feet on the floor has been repeatedly noted, e.g. in relation to industrial furniture, of which it was remarked by Gilbreth and Gilbreth (1919) that "if every manager were made to sit for a certain number of hours today with his feet hanging, there would be an enormous increase in the number of footrests in our industrial plants tomorrow morning". Apart from the discomfort in the lower limbs, this position is more fatiguing than when the feet are flat on the floor; Lundervold (1951 a, b) found that the onset of muscular activity in the back muscles was hastened when the feet were unsupported. A Ministry of Labour pamphlet (1945) and a similar Danish publication (Schleisner 1952) recommend that seat heights should be slightly less than the height of the underside of the thigh. An intensive American study by Bennett (1928) maintained that the seat must not be so high as to cause any pressure under the thighs when the feet rest squarely on the floor, and, further, that there is little objection to its being two or three inches lower than this provided that there is space for free foot movement. Both Hooton (1945) and Akerblom (1948) agree that seat heights should be low so as to suit shorter subjects "in the hope that those with long legs will also find them comfortable" (Akerblom 1948, p. 158). The extreme view is represented by the dictum of Yu-T'ang Lin (1937), unsupported however by scientific evidence: "the lower the chair is, the more comfortable it becomes".

Some authors have suggested that seats which are too low may not be altogether desirable. Keegan (1953), who approached the problem clinically with reference to the causes of low back pain, considers that an acute angle between trunk and thigh should be avoided, and suggests a minimum angle of 105°. Lundervold (1951 a, b) found that the onset of muscular activity in the back muscles was hastened when the seat was lowered so that the knee angle was decreased from a right angle to an acute angle. Seventy years ago it was suggested by Staffel (1884) on theoretical grounds that a chair seat should slope forwards to reduce the bending of knee and hip joints which was thought to impede the circulation; however, more recent studies of pelvic position in sitting and of circulation to the lower limb suggest that interference with blood supply to the legs, due to knee and hip flexion, is much less than had been imagined (e.g. Basler 1929).

There is a further objection to the general provision of low seats. It is readily seen, by a simple demonstration, that the lumbar concavity cannot be maintained when the hamstrings are stretched beyond a certain extent. This limiting amount of stretch occurs in the sitting position approximately when the angle between the thigh and trunk is less than about 90° and the knee is flexed, or when the angle between the thigh and the trunk is 90° and the knee extended. Thus the taller person, sitting on a seat which is at a low height in order to accommodate a shorter person, is at a disadvantage in that he may not be able to attain concavity of the lumbar spine. In the extreme situation he may be compelled to adopt a posture involving considerable lumbar convexity.

It appears therefore that there is some conflict between the need for a low seat, in order to accommodate as wide a range of the population as possible without under-thigh pressure, and the need to avoid excessive hip flexion and the lumbar convexity which may accompany it. More than a single seat height may be necessary to cover the range from the tallest male to the smallest female; ideally, the former would require a 19-inch seat height (99th percentile) and the latter a 15-inch seat height, even when wearing shoes.

Stable and comfortable postures can be achieved on seats tilted at various angles forwards and backwards, given satisfactory positions of the arms and legs, of the back-rest (when used) and of the table or other working surface. It may well be, however, that some of these postures on sloping seats are only comfortable for relatively short periods of time. With tilted seats, the ideal height of the front of the seat is not necessarily the same as for horizontal seats. The ultimate criterion of suitability is the absence of significant pressure between the soft tissues of the posterior aspect of the thigh and the seat itself.

The lower-leg dimension referred to above is to be regarded only as an initial guide, for it will be appreciated that the posture actually adopted in the sitting position on a seat of any given design (e.g. given seat tilt and height) is likely to be different from the standard anthropometric posture adopted for determining the seat height initially. Hence, to use the raw anthropometric data unmodified in the light of experimental work may bring about a discrepancy between the range of persons for whom the seat was designed as compared with the range of persons who can sit on the seat without undue pressure on the soft parts of the thigh.

Seat height above ground or above foot-rest level is only one of the factors which determine efficiency and comfort in the working position. Equally important is the relation of the seat to the working surface (see §11 Table Height).

§ 4. SEAT DEPTH

For seat depth, the primary considerations are that the ischial tuberosities should be supported and that, when the back-rest is in full use, there should be adequate clearance between the back of the calf and the front of the seat in order to avoid the discomfort due to pressure behind the knee by the edge of the seat. The maximum seat depth is determined therefore by the distance between the posterior surface of the calf and the plane tangential to the back in the sacral region when the body is in the upright seated position. This measurement is somewhat longer than the seat need be. The front edge of the seat needs to be less than 3 or 4 inches behind the knee joint for small children and less than 6 to 8 inches for large adults (Bennett 1928), otherwise the seat depth is too small and uncomfortably confining.

The minimum seat depth is governed by the position of the ischial tuberosities not only when the trunk is upright and in contact with the back-rest, but also when, allowing for changes in position, the trunk is inclined backwards in contact with the back-rest and the buttocks are some distance in front of the seat back. Hooton (1945) contended that "the depth of the seat should be selected to provide for the fact that most individuals do not put their buttocks against the back", but it was pointed out by Akerblom (1948) that this position may be assumed on account of unsatisfactory dimensions or other features of ill-constructed chairs. For example, it is a posture commonly taken up when seat height is too great, presumably in order to avoid the discomfort occasioned by underthigh pressure.

In a sample of 285 British males the average for the distance from the popliteal angle to the sacral plane was 17·9 inches with a standard deviation of 0·9 inches. A seat depth of 15 inches measured from the front edge of the seat to the projected line of the back-rest would be suitable therefore for over 99 per cent of men and by extrapolation (for no figures are available for this measurement in females) for 99 per cent of women.

§ 5. SEAT WIDTH

Darcus and Weddell (1947) came to the conclusion that, for seat width, it is necessary to make an allowance for lateral movement beyond the requirement of accommodating "subjects of maximum dimension". The minimum width is clearly determined by the need for support of the ischial tuberosities, but for stability of posture a relation to the trochanteric width appears to give a more realistic estimate. Few chairs of the simple office or domestic type are inadequate in this respect but many factory and laboratory seats are too narrow for comfort and sometimes even for stability.

Thigh breadth in a British male sample of 115 seated subjects was: average, 15·9 inches; standard deviation, 1·1 inches. If some soft tissues are permitted to overlap slightly the sides of the seat, a seat width of 16 inches will suit all except the broadest of individuals; where chair arms are provided, however, the width between them needs to be at least 19 inches.

§ 6. Tie Rail

Associated with seat height and depth is the question of the mechanics of rising from a seat. It is important to bring the feet under the body in order to reduce muscular effort in rising (Keegan 1953), especially for older people. A seat short in depth is favourable to this movement. An easy movement can also be achieved if there is no obstruction, between the front legs of the chair, to the free movement of the feet to a position under the front of the seat. In terms of design, horizontal struts placed between the front legs of a chair for strengthening purposes should be avoided if possible. If they are essential for a particular design, they should be restricted in position to the upper few inches of the chair legs. Experiments (unpublished) by the Furniture Development Council have suggested that there is little loss in structural strength until horizontal struts are raised to a point *within* the topmost fifth of the total length of the leg of the chair.

§ 7. Trunk Stabilization

The ischial tuberosities are not flat but curved, bony projections, as can be readily perceived by palpation. The curve of the ischia is of fairly large radius, and the soft tissues of the region serve as 'packing', helping to distribute the pressure over the ischial region. The weight bearing base of the trunk, in the sitting position, is therefore a long narrow rectangle with the ischial tuberosities as its left and right sides. Upon this the trunk balances, but requires stabilization in the antero-posterior plane. Stabilization is achieved in various ways demanding different degrees of effort:

(*a*) The trunk may be maintained upright in a condition approaching unstable equilibrium, by the continual interplay of the various muscles correcting sway away from the position of balance; in other words, by the expenditure of energy in lowgrade intermittent muscular activity;

(*b*) the trunk may be slumped forward so that the strain is borne largely by the spinal ligaments and gluteal muscles;

(*c*) the trunk may be maintained in more stable equilibrium by the use of an external support such as a back-rest, stability depending largely on friction between the buttocks and seat and between feet and floor;

(*d*) the arms may be employed as props in various ways; when there is complete locking, for instance of head against hand, elbow against thigh or desk, feet against floor etc., the condition approaches stable equilibrium.

Many people adopt a working position in which the trunk is supported by the arms placed on the desk or some part of the machinery at which they work, and it can be readily demonstrated electromyographically that in such positions many muscles of the trunk and limbs may become relaxed (Floyd, unpublished).

The muscles of the back, especially those in the lumbar region (the lumbar erectores spinae) contract when the subject is sitting upright without back support and with the feet on the floor. To sit upright in this way without trunk support is possibly more fatiguing to the back muscles than is standing upright, since activity in the erectores spinae muscles is certainly somewhat greater in the sitting position (Floyd and Silver 1955). These muscles do not usually relax until the subject leans over backwards in an extreme, almost unstable and uncomfortable position. They relax when the vertebral column is allowed to flex forwards so that Fick's round-back position is attained (Akerblom 1948, Fick 1911, Floyd and Silver 1955). They also relax when an external support takes the weight of the trunk.

There are thus several ways in which the muscular fatigue of sitting may be diminished. The trunk may be supported: (i) by a back-rest which has the advantage that it does not interfere with operations in front of the body, (ii) by the arms, or (iii) at the front of the body, e.g. by the chest. Alternatively, the trunk may be slumped forwards into the round-back position, in which event the strain is borne by the ligaments of the vertebral column instead of the muscles; this posture, if maintained for a long time, may be painful or permit ligamentous injury.

§ 8. THE BACK-REST

To allow the first of these three stances, chairs should incorporate back-rests satisfactory in position and shape. The back-rest must be rigid to afford adequate support for that part of the trunk weight acting on it; this does not mean that it must necessarily be fixed, for a spring-loaded support may be successful if the spring is noiseless and is strong enough to resist practically the full weight of the body applied to it. The back-rest must not restrict the movement of the vertebral column or of the arms; thus complete support for the whole of the back is excluded. A back-rest fitting the lumbar concavity allows free movement at the thoraco-lumbar junction where the greatest amount of spinal movement occurs (Bowen 1953, Gallois and Japiot 1925). Darcus and Weddell (1947) considered that when a correctly designed lumbar support is provided, further support in the upper region of the back is unnecessary. Akerblom (1948) demonstrated electromyographically that a support in the lumbar region is as effective as a combined lumbar and thoracic rest, while similar studies by Floyd (unpublished) and Lundervold (1951 a, b) show that a single support is most effective in the lumbar zone and least effective in the region of the shoulder blades.

The following explanation would appear to be the interpretation of the electromyographic evidence already cited. When a back support is applied high up in the back the activity in the lumbar erectores spinae muscles is diminished as compared with the erect position without back support. If the subject now relaxes the lumbar muscles by slumping, while retaining the high back support, muscle activity ceases in the lumbar region. The subject is now sitting with fully flexed lumbar spine and with the back supported only high up at the mid-scapular region. When, however, the back-rest is provided in the lumbar region, support may be obtained and the muscles relax before the full degree of trunk flexion is reached. In this position further flexion of the vertebral column to the full flexion position is being prevented by the lumbar support. The ligamentous strain is less than would occur with full flexion and without lumbar support. The degree of flexion reached before lumbar support and relaxation are obtained obviously depends upon the design of the chair and the position of the subject upon it. The design of chairs should be such as to permit the use of a lumbar support in this way, i.e. to provide support for the trunk before full flexion of the spine under gravity is reached. It should be noted here that the Akerblom chair (Akerblom 1948, 1954) provides, basically, a lumbar support which preserves the lumbar concavity for those persons who possess it. By adjustment of the position of the ischia on the seat of the chair it is possible to reach the relaxed position just described in which lumbar support is given while there is a mild degree of lumbar convexity, but less than in the full flexion position.

Thus the anatomical and physiological evidence points to a lumbar support as necessary in order that the lumbar erectores spinae muscles may be relaxed without full flexion of the trunk, so enabling a relaxed position to be achieved without undue ligamentous strain. Considerable range of movement, probably sufficient for most tasks carried out at a desk or table, is allowed at the thoraco-lumbar junction while use is made of the lumbar support. The range of movement would be restricted were a support provided at a higher level in the back. The support is probably most effective when provided within the range of the 2nd to the 5th lumbar vertebrae.

§ 9. HEIGHT, CURVATURE AND ANGLE OF BACK-REST

When a back-rest is low enough to come into contact with the sacral region, its effect on the occupant of the chair is to slide him forward on the seat. The lower portion of the back-rest should therefore be clear of the sacral region so that the sitter can comfortably oppose his lumbar region to the back-rest. An adequate criterion for determining the height of the upper edge of the back-rest is the height of the shoulder blades, the inferior angles of which should be clear of the back rest in a working chair. Measurements of the height of the sacrum and shoulder blades above the seat of the chair are not available for the British population, but observation suggests: (i) that a distance of 8 inches above the seat allows the edge of a back-rest to clear the sacral region, and (ii) that a distance not greater than 13 inches above the seat allows the upper edge of such a back-rest to clear the shoulder blades of most people.

It would seem reasonable to provide a support with an anteriorly convex surface in sagittal section, to help in accommodating persons of different size, as well as to assist the fit of the back-rest into the lumbar region and prevent undue pressure at the upper and lower edges of the back-rest. The pressure applied to the back-rest should be distributed over as large an area as possible, to achieve which the transverse curve should conform to the lateral curvature of the lumbar region of the body (Darcus and Weddell 1947); Bennett (1928) found too deep a curve unsatisfactory. As an extreme example, a rest, designed to fit the back very closely in order to achieve stability in a naval chair, had a radius of horizontal curvature of $7\frac{5}{16}$ inches. For general use a radius of not less than 12 inches and usually of 16 inches to 18 inches is to be preferred. Some upholstery is also desirable, especially as it acts as a cushion in improving the fit of the lumbar region into the back-rest.

The angle of slope of the back-rest (measured in the sagittal plane) required for a satisfactory fitting varies from individual to individual; it also varies according to the height at which it is situated above the seat and the purpose for which the chair is to be used. Morant (1947), in a study of aircraft seats, favoured a back-rest angle of up to 110° for the alert position and of 110°–125° for a comfort position; the average slope found by Lay and Fisher (1940) for a position of comfort in an automobile, based on a study of 250 American adults, was 111·7°. For a lumbar back-rest 95°–100° appeared optimal for the alert position in 500 subjects in another investigation (Roberts *et al.* unpublished) concerned with seating for school children in Middlesex.

A close approach to a satisfactory back-rest is that devised by Akerblom (1948, 1954), saddle-shaped in appearance. The anteriorly convex sagittal profile facilitates the accommodation of persons of different sizes, the lateral curvature is not restricting while the dual angle of slope resulting from the convex sagittal profile allows it to be used both in the alert and the relaxed positions.

§ 10. SHAPE AND SLOPE OF SEAT

Various shapes of seat have been proposed from time to time, from a saddle-shaped seat to one which was moulded to fit the backside and sloping slightly backwards. Attempting to fit the soft tissues of the thighs, for reasons stated above, is purposeless, while support at the side of the ischia was found objectionable even by those whom it fitted (Bennett 1928). The bucket-shaped or 'ploughman' seat with a perineal elevation was condemned strongly by Darcus and Weddell (1947) who advocated that the part of the seat "supporting the ischial tuberosities should be flat and disposed horizontally". The chief advantage of the unshaped seat is that there is less risk of localization of pressure on tissues ill-adapted to withstand it; the only advantage of the shaped seat is that it *may* utilize more of the ischial area for support, but variations in size and shape of this area from individual to individual are considerable, so that any such shaping is of dubious value. It is better therefore for the seat to be substantially plane.

In order that pressure may be concentrated over the ischial tuberosities and not distributed para-ischially, it is important that the seat should be hard; a slight amount of upholstery may help to achieve this end. The softer the seat the greater the tendency for the pressure to be widely distributed. It is for this reason that chairs of the canvas seat type, one popular form of the stacking chairs so widely used, are to be condemned; the pressure in such 'numbumb' seats is invariably distributed widely over the soft tissues, leading to discomfort and anaesthesia of the skin of the buttocks and thighs.

As regards the slope of the seat, again differing preferences have been expressed, from a somewhat unpractical forward slope proposed by Staffel (1884) through more complex profiles (e.g. Bennett 1928, Lay and Fisher 1940, Weddell and Darcus 1947) to the backward slope of 3–5° favoured by Akerblom (1948) for mechanical reasons. An advantage of the backward slope is that the trunk tends to be held back in such a position as will make full use of the back-rest. Arguments in favour of the horizontal seat are that there is a less acute angle between thighs and trunk, the onset of activity in the back muscles is hastened if the seat is sloped and retarded if it is horizontal as shown electromyographically by Lundervold (1951 a, b), that there is no tendency to hold the body in a particular stance and thus changes of position are facilitated. Indeed, the last is a most important consideration; the lengths of the spinal segments and the position and degree of the spinal curves vary considerably from individual to individual, and therefore the optimum back-rest position and angle are not the same for all.

Normal postural adjustment to a fixed back-rest is by forward or backward movement on the seat. This adjustment may be restricted by a sloping or shaped seat. With a plane back-rest of fixed position this may lead to local pressure on the back at the upper or lower edge of the back-rest, with ensuing discomfort. Certain types of clerical work, among other activities, demand an upright or forward leaning trunk, which precludes the use of the back-rest in chairs of conventional design. It may well be that when the person using the chair spends a considerable proportion of his time in such operations, a backward tilt to the seat is a disadvantage. A horizontal seat or one with a slope of less than 3° is probably more suitable for these situations. The backward tilt of the seat appears to be of advantage only in the situation when there is forward pressure on the trunk from a back-rest. If the trunk is kept largely upright and unsupported, or slumped and unsupported, as occurs in sitting on a bench, there is no tendency to slide on the seat, and the seat for mechanical reasons should be horizontal.

§ 11. TABLE HEIGHT

The danger of postural defects arising from habitual use of badly designed tools and furniture was pointed out under 'Posture'. This applies especially to the use of too high a table. The height at which the table-top should be situated is functionally related to the position of the elbow. How far the elbow should be above the table varies according to the type of work to be done, and with the amount and direction of the forces to be exerted. Ideally "the worker's elbows will bear the same relation to the work place when he is sitting as they would do if the work place were properly adjusted for him to do standing work" (Gilbreth and Gilbreth 1919). Foı a given arm position, the height of the elbows in a sitting individual depends on the position of his trunk and the height of the surface on which he is seated; hence the necessity of considering the chair and table as a single unit.

In a study of typists who had personally adjusted their chairs to suit themselves, there was a significant positive correlation of chair height with table height and of elbow height with table height. There was no correlation, however, between chair height and lower-leg length or stature (Floyd *et al.* unpublished). Obviously, a primary consideration in adjusting their chairs was the desire to bring the elbow into a satisfactory relationship to the working surface. Physiological evidence supports this empirical observation.

For clerical work, such as is commonly carried out in offices at desks or similar working surfaces, electromyographic studies by Lundervold (1951 a, b) indicate that it is probably desirable that the elbows should be at about the level of the working surface when the trunk is erect, the shoulders are down (i.e. relaxed), the arms are hanging freely and the elbows are in a natural position beneath the shoulders, i.e. neither abducted or adducted. This makes it possible for the forearm to be approximately horizontal when simple movements over the working surface are made such as are involved in writing, moving papers and other activities of what may be called 'desk work'. When the elbows are much below the level of the working surface it is found that a cramped position is often taken up for writing, and the edge of the working surface exerts pressure on the forearms. One or both shoulders will often be raised in order to bring the elbows and forearms above the working surface. Muscle activity may be maintained in this way, as static effort, for considerable periods of time. There is plenty of clinical evidence to demonstrate that these conditions are undesirable. Hence they should be avoided.

Vertical distance from the floor to the undersurface of the table, or to any supporting rail under which the thighs are placed, must be sufficient to allow clearance of the upper surface of the knee and thigh when shoes are worn, and to allow easy access. The distance of the undersurface of the table above the chair seat therefore requires to be rather greater than thigh thickness. Hence, if the height of the working surface above the seat is to be based on the distance between elbows and ischia in the seated position, restrictions are imposed on the maximum allowable thickness of table top including that of any supporting rail.

It can be seen from the figures in Table 2 that it is not always feasible to meet the theoretical requirements. The elbow height of the smallest man (1st percentile) sitting on a 17-inch chair will be 23½ inches, indicating a table-top at that height; the thigh thickness of the largest man will be 7½ inches, so that he will require an undertable vertical clearance of 24½ inches. If more than one size of table is not to be provided, compromise on the requirements of individuals at the extremes of the statistical distributions is necessary. In practice, observation shows that most people, even when working at tables of low height, bring the upper arm forward, i.e. flex the shoulder, so that the elbow is raised 1–2 inches. A table height of 27½ inches will, in these circumstances, suit at least the taller half of the population, while a table thickness of not more than 2 inches will allow the thighs of all to be accommodated.

Horizontal clearance underneath the table-top is also important; there should be no obstruction to free movement of the knees. If the knee-hole space is clear for a horizontal distance of 18 inches at a height of 25 inches from the ground, it will allow the tallest person to sit close to the desk, and will allow most people to cross the knees. This horizontal clearance should increase to 24 inches at ground level to accommodate the legs and feet when stretched forward.

Table 2

Measurements Pertinent to Table Construction

Sample	Sample number	Measurement	$\bar{x}$	σ
British male sample	61	Height of elbow above seat	8·71	1·04
,, female sample (typists)	63	,, ,, ,, ,, ,,	8·66	1·04
,, ,, ,, (students)	25	,, ,, ,, ,, ,,	9·0	1·15
,, male sample	75	Thickness of thigh	6·1	0·6
,, ,, ,,	75	Distance of front of abdomen from front of knee	14·1	1·1
,, ,, ,,	75	Height to patella top	19·9	1·0

$\bar{x}$=mean ; σ=standard deviation : all dimensions in inches.

In the light of the arguments set out above, it is evident from available anthropometric data that all 30-inch working surfaces are too high for the 18-inch chairs commonly used with them, while the 18-inch chairs themselves are too high for general use without a footrest. Lower table and chair heights are indicated. Lack of familiarity with chairs and tables of the smaller dimensions to which the evidence points may give the impression that they are out of scale, especially by comparison with other items of furniture. A disadvantage of the lower table heights suggested, which is more apparent than real, lies in their diminished suitability for work in a standing position. But, for the majority of people, tables of height 30 inches are already too low for comfortable standing work, for which heights of up to 36 or 38 inches may be required. It seems impossible to provide a table generally suitable for both standing and sitting work. However, the situation arises on occasion that tables do have to be used for both purposes, in which case the most satisfactory solution is to raise the height of the chairs and to provide stable footrests in order to maintain the metrical relationships of elbow, working surface, chair seat and floor discussed already in the paper.

§ 12. CONCLUSION : APPLICATION OF BODY MEASUREMENTS

It is obvious that there is already an appreciable amount of experimental and empirical biological evidence pertinent to the design of chairs and tables, though there still remain many details requiring further investigation. Wider application of the principles to which the evidence points would lead to improvement in the comfort and efficiency of accommodation of furniture users.

The foregoing review of the underlying anatomical and physiological considerations demonstrates clearly the important role of dimensions of the body in furniture construction. In brief, the design of chairs and tables may be envisaged as comprising several dimensional components. The height of the front of the seat and height of underside of table form one such component, based on the measurements of the leg. The height of the back-rest and the height of the table surface form the second component, depending on body dimensions measured vertically from the part of the seat actually used for support. These two components are connected by the seat length, again derived dimensionally. They are inter-related also through the angle of slope of the seat. To these it is necessary to add a functional component, viz, the use to which the furniture is to be put; upon this is dependent the slope of the back-rest, and it influences the choice and application of the measurements underlying the other components.

In applying anthropometric measurements in problems of furniture design, there is need for caution on two scores. First, it is essential that proper account be taken of the variability of human beings. Each dimension of a chair or table poses its own problems. For example, in the distance of the undersurface of the table above the chair seat, the largest person who will use the furniture needs to be catered for. For seat depth the dimension of the smallest person needs to be employed. Published anthropometric data usually include information on variability of body dimensions. Which percentile of the population is to be regarded as the 'smallest' or 'largest' is a problem for the individual designer. It is also an economic problem. A range from about the 5th to the 95th percentile has been used by many workers (e.g. Darcus and Weddell 1947, Hooton 1945, McFarland *et al.* 1953)*.

Secondly, there is an important difference between descriptive anthropometric measurements taken on the static body often in a fixed unnatural

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*In terms of the mean ($\bar{x}$) and standard deviation (σ), and on the assumption of a Gaussian distribution, the range from the 5th to the 95th percentile is :

$$\bar{x}-1{\cdot}66\sigma \text{ to } \bar{x}+1{\cdot}66\sigma.$$

position and the functional measurements referring to the body in a more usual posture. For instance, as a basis for dimensions of table-tops, it is necessary to know not only details of forward and lateral reach when the subject is sitting upright, but also how far he can reach by bending and twisting the trunk, and what tasks he can and does do with his hands at various distances away from his trunk. The translation of descriptive into functional data presents problems, the successful solution of which frequently lies in the experimental approach.

Data given in anthropometric reports and handbooks of ‘ human engineering ’ are not to be used uncritically therefore. Those wishing to apply them need first to understand the basic principles underlying their use. It is as a step towards this end that the present paper has been written.

Les principes généraux dérivés des études anatomiques, physiologiques et clinques du mouvement et du maintien peuvent s'appliquer au dessin des meubles. On s'occupe ici de ce problème par rapport aux dimensions et à la forme des chaises et des tables destinées à l'usage domestique ou bien dans les bureaux. Les conclusions suivantes résultent de l'étude de ce qu'on a ecrit sur ce sujet et des propres recherches des auteurs :

(1) Lorsqu'on est assis, il faut pouvoir changer de position. Une bonne chaise devrait le permettre.

(2) Lorsqu'on est assis, le poids du tronc doit être soutenu par les tubérosités ischiatiques, ce qui admet probablement du confort maximale. Les cuisses sont, du point de vue anatomique et physiologique, mal adaptées à soutenir le poids du corps.

(3) Donc, la hauteur d'un siège de chaise ne devrait point dépasser la longueur de la partie inférieure de la jambe de la personne la plus petite qui utilisera la chaise. Il y a pourtant quelque difficulté à concilier le besoin d'un niveau de siège assez bas pour accommoder les personnes plus petites et le besoin d'éviter une flexion des hanches excessive et la convexité lombaire qui en résulterait, chez les personnes plus grandes assises sur une chaise basse. On pourrait avoir besoin de plus d'un niveau de chaise pour suffire à la gamme entière entre le mâle le plus grand et la femelle la plus petite.

(4) La profondeur maximale du siège qui s'accorde avec le confort se détermine suivant la longueur des cuisses des personnes plus petites qui utilisent la chaise. La largeur du siège est indiquée assez exactement par les dimensions trochantériennes.

(5) Un siège en gènèrale aplani est préférable à un siège formé ou moulu à la forme du séant. Un penchant vers le dos de la chaise de jusqu'a à cinq degrés peut être utile pour certains buts.

(6) La mécanique de l'action de se lever d'une chaise défend, dans la construction d'une chaise, des barres horizontales ou d'autres obstacles entre les jambes de devant.

(7) Un dos de chaise qui soutient le dos de la personne assise diminue les mouvements musculaires exécutés par le tronc, mais il ne devrait point restreindre la mobilité de la colonne vertébrale ou des bras. Un soutien dans la région lombaire limité par le second et le conquième vertébre lombaire permet un degré suffisant de mouvement libre. Un dos de chaise en forme de selle, pareil a celui qu'a recommandé Akerblom, donne un soutien qui satisfait ce besoin. Les dimensions et les angles de penchant sont considérés dans ce papier.

(8) La table et la chaise forment un seul tout anthropométrique. L'hauteur de la table est corrélée étroitement à l'hauteur des coudes. Les coudes devraient être à peu près au niveau de surface destinée au travail. L'espace entre le dessous de la table et le siége de la chaise doit excéder d'un petit peu la grosseur de la cuisse.

Allgemeine Erfahrungen, die bei anatomischen, physiologischen und klinischen Studien gewonnen wurden, lassen sich für den Entwurf von Möbeln nutzbar machen. Diese Arbeit beschäftigt sich mit diesem Problem in Bezug auf die Maße und die Form von Stühlen und Tischen für Büros und für den allgemeinen häuslichen Gebrauch. Aus einer Sichtung der Literatur und aus den Untersuchungen der Verfasser sich folgende Schlüsse ziehen :

(1) Beim Sitzen sind Aenderungen der Körperhaltung wichtig. Ein guter Stuhl sollte diese erlauben.

(2) Beim Sitzen sollte das Gewicht des Körperstammes hauptsächlich von den Sitzbeinhöckern getragen werden. Dies führt wahrscheinlich zur grössten Bequemlichkeit. Die Schenkel sind anatomisch und physiologisch ungeeignet, das Körpergewicht zu unter Stützen.

(3) Daher sollte die Höhe der Sitzfläche des Stuhles nicht grösser sein als die Länge des Unterschenkels der kürzesten Person, die diesen Stuhl benutzt. Es besteht jedoch ein Konflikt zwischen dem Bedarf nach einem Sitz, der tief genug ist, um kürzeren Personen zu entsprechen und der Notwendigkeit, zu vermeiden, dass längere Personen beim Sitzen auf einem so tiefen

Sitz zu einer zu grossen Hüftbeugung und damit zu einer konvexen Haltung der Wirbelsäule gezwungen werden. Mehr als 1 Sitzhöhe dürfte erforderlich sein, um den Unterschieden zwischen dem grössten Mann und kleinsten Frau gerecht zu werden.

(4) Die für Bequemlichkeit erforderliche grösste Sitztiefe ist bestimmt durch die Länge der Oberschenkel der kürzesten Person, die den Sitz benutzt. Die Breite des Sitzes muss der Breite des Körpers in Trochanter-Höhe entsprechen.

(5) Ein im wesentlichen flacher Sitz ist einem Sitz vorzuziehen, der der Sitzpartie des Körpers angepasst ist. Eine Rückwärtsneigung der Sitzfläche bis zu etwa 5° ist in manchen Fällen zu empfehlen.

(6) Die Mechanik des Aufstehens von einem Sitz erlaubt keine horizontalen Streben oder andere Hindernisse, die zwischen den Vorderbeinen eines Stuhles angebracht sind.

(7) Die Aktivität der Stamm-Muskeln beim Sitzen wird durch eine Rückenlehne herabgesetzt ; die Rückenlehne sollte jedoch nicht die Bewegungsmöglichkeit der Wirbelsäule und der Arme behindern. Unterstützung in der Lendenwirbel-Gegend im Bereich des 2 bis 5 Lendenwirbels erlaubt freie Bewegungen. Eine sattel-artige Rückenlehne—wie die von Akerblom empfehlene—gibt befriedigende Unterstützung. Grösse und Winkel der Neigung wurden in der Arbeit besprochen.

(8) Tisch und Stuhl bilden eine einzige anthropometrische Einheit. Die Tischhöhe ist eng an die Ellbogenhöhe gebunden. Die Ellbogen sollten ungefähr in der Höhe der Arbeits-Ebene liegen. Der Zwischenraum zwischen der Unterfläche des Tisches und der Sitzflächenhöhe sollte etwas grösser sein als die Oberschenkeldicke.

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A STUDY OF ACCIDENTS IN RELATION TO OCCUPATION AND AGE

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A study is reported in which accident rate is related to age and occupation. Age distributions of observed accidents occurring during a four-year period to manual workers in each of nine jobs are compared with distributions expected on the assumption that job differences do not result in differences in fluctuations with age of accident rates. Three significant differences between observed and expected distributions are obtained. These relate to the jobs of Electrician, Miller and Grinder, all of which are jobs in which mainly younger workers are normally employed. The median ages of those employed in nine jobs are correlated with the extents to which accidents in the upper age groups are more or less numerous than expected. This correlation is significant, and indicates that older workers in jobs normally occupying younger workers tend to have more accidents than expected. Fluctuations in accident rates with age are concluded as being a function of the type of work studied. The results of the study are thought to reflect the difficulties of older workers in meeting the demands of certain types of work.

§ 1. Introduction

Previous research into the relationship between accidents and age (as summarized, for instance, by Speakman 1956) has often produced results which, prima facie, seem to be contradictory. Some studies have shown accidents to rise with age, others have shown them to fall, and others again have revealed little age trend. In commenting upon the difficulty of interpreting accident statistics in relation to age, King and Speakman (1953) note that few studies have attempted to control the type of work to which data apply.

It is tacitly assumed in most textbooks of industrial psychology that job success, of which freedom from accidents is often regarded as a useful criterion, is a function largely of the worker's capacity to meet the demands of his job. If these demands are too great then accident rates may be higher than if the demands are less stringent.

If, as has often been suggested in recent years, an older person's capacity to meet the demands of certain types of work is in some ways lower than that of a younger person, then it might be expected that this would be reflected in his increased liability to accidents. The classical study in coal mining, by Vernon and Bedford (1931), has provided information which strongly suggests that accidents sustained by workers of different ages might, in part, be a function of certain environmental conditions. If the relationship between accidents and age is influenced more generally by other job demands and conditions, then different accident rates might be demonstrated in the upper age groups of different jobs.

If accident rates in certain jobs increase with age to a greater extent than in others, another effect might be expected. In those jobs in which accident rates are most severe in the upper age groups, the difficulties facing older workers might result in a tendency to leave. This would lead to a preponderance of younger workers in these jobs. Progressive selection of this kind has been discussed recently by Welford (1957) in relation particularly to deterioration in output. It has also been advanced as an interpretation of the finding that an hierarchy of jobs, in terms of the ages of those employed on them, exists in the engineering industry. This hierarchy was consistently found in different firms and in different areas of the country, and, in one firm, over a period of eight years (Murrell *et al.* 1957, Murrell and Griew 1958). If this interpretation is correct, and if the foregoing argument is valid, those jobs in which a preponderance of younger workers exist should also be those in which older workers sustain more accidents than would otherwise be expected.

The issues raised in the foregoing discussion would be clarified if answers to the following two questions could be obtained. The first question is, " do accident rates in certain jobs increase with age to a greater extent than in others? " The second question is, " are jobs in which accident rates in the upper age groups are particularly high, also those in which a preponderance of younger workers is to be found? " The aim of the study reported here was to provide answers to these questions.

§ 2. Method

The study was carried out in a large factory manufacturing piston and ' turbo-prop ' aero-engines. Age distributions were constructed, for each of a number of jobs, of all reportable accidents occurring to manual workers between 1st January, 1953 and 31st December, 1956. Accidents occurring to workers sustaining more than two accidents during the period were disregarded so as to reduce the possible misleading influence of a small number of ' accident prone ' individuals. This involved discarding data on thirteen accidents out of a total of 281 which occurred during the period. For each job and for each of six age groups within jobs, an accident rate was calculated. This was done by dividing the number of observed accidents in each age group by the average number of workers to whom accidents could have occurred. The average number of workers to whom accidents could have occurred was taken to be the number of workers present on 1st January, 1955, the central point of the four-year period. This estimation was necessary, as the task of determining more reliable averages would have involved reconstructing the payroll of the company at many different points during the period, and this would have been a prohibitively large task. It is thought, in any case, that the estimation was justified, in view of the stable age structure which had already been found to exist in the industry, and to which reference has already been made.

In order to test the significance of the differences in the fluctuations with age of accident rate in the different jobs, the observed age distribution of accidents in each job was compared with that which would have been expected on the assumption that job differences do not result in differences in fluctuations with age of accident rates. The calculation of expected distributions was as follows. The number of workers in an age group on a job was multiplied by the average number of accidents occurring to workers in the age group during the four-year period throughout the firm. In view of the differences between overall accident rates of jobs, these products had to be multiplied by a factor which weighted them according to the overall accident rate of the job. This factor was obtained by dividing the total number of observed accidents in the job during the period by the sum of the products previously calculated for the different age groups of the job.

If the average numbers of workers employed in the six age groups of a job are

$$n_1, n_2 \ldots\ldots n_6;$$

and the average numbers of accidents sustained by workers in the six age groups throughout the firm during the period are

$$r_1, r_2 \ldots\ldots r_6;$$

the expected numbers of accidents occurring in the six age groups of the job during the period, unweighted for different overall accident rates of jobs, will be

$$n_1 r_1, \; n_2 r_2 \ldots\ldots n_6 r_6.$$

Let the sum of these values be $\sum (nr)$.

If the observed numbers of accidents during the period in the six age groups of the job are

$$o_1, o_2 \ldots\ldots o_6;$$

and the sum of these values is $\sum(o)$,

then the weighting factor will be $\dfrac{\sum(o)}{\sum(nr)}$.

Hence, the expected numbers of accidents occurring in the six age groups of the job during the period, weighted according to the overall accident rate of the job, will be

$$\frac{\sum(o)}{\sum(nr)} n_1 r_1, \frac{\sum(o)}{\sum(nr)} n_2 r_2 \ldots\ldots \frac{\sum(o)}{\sum(nr)} n_6 r_6.$$

The goodness of fit of the observed and expected age distributions of accidents in each job were compared by using the chi-squared test.

Finally, in order to determine in which jobs accident liability in the upper age groups was greatest, the following calculation was undertaken in the case of each job. The expected number of accidents (E) in the 45 and over age group was subtracted from the observed number of accidents (O) in this age group. This gave an $(O-E)$ expression which indicated the difference between observed and expected accident frequency in the age group, and the ' direction ' of this difference. The expected number of accidents in this age group was different in each job. In order to obtain expressions which reflected the *extent* to which accidents were more or less frequent than was expected, and in order that these expressions would be comparable, each $(O-E)$ value was divided by the relevant E. This gave a series of $(O-E)/E$ expressions. A job in which this value was large and positive is one in which accidents in the upper age group are much more numerous than would have been expected; a large negative value indicates the opposite. These values were ranked from largest positive to largest negative, and the median ages of workers employed in the same jobs on 1st January, 1955, were also ranked. The two sets of rankings were then correlated according to Kendall's ranking method (Kendall 1948).

§ 3. RESULTS

Table 1 shows the observed numbers of accidents occurring during the four year period, by age group and job, and (in brackets) the average numbers of workers in the different age groups and jobs to whom accidents could have occurred. Mean annual accident rates, calculated from data in Table 1, are given in Table 2. It is evident that fluctuations with age in accident rate vary from job to job. Table 3 gives the observed and the expected age distributions of accidents in the different jobs, together with the values of chi-squared calculated for each job. Apart from those jobs classified as "Miscellaneous", all of which showed too few accidents during the period to warrant separate treatment, three significant chi-squareds are observable. These relate to the jobs of Electrician, Miller and Grinder. In each of these cases more accidents appear to have been sustained by workers in the upper age groups than would have been expected. Each of these jobs is one in which younger workers are normally employed.

Table 1

Accident Frequency by Age Group and Job

Job	21–28	29–36	37–44	45–52	53–60	61+	Total
Electrician	2	1	3	4	1	0	11
	(34)	(47)	(27)	(18)	(8)	(3)	(137)
Turner	3	1	3	2	1	0	10
	(28)	(51)	(48)	(29)	(10)	(5)	(171)
Miller	3	1	4	5	1	0	14
	(67)	(65)	(52)	(33)	(14)	(4)	(235)
Grinder	2	1	4	5	1	1	14
	(51)	(63)	(64)	(34)	(16)	(6)	(234)
Fitter (skilled)	5	14	11	7	12	4	53
	(67)	(100)	(121)	(123)	(99)	(43)	(553)
Fitter (semi-skilled)	1	3	2	2	4	1	13
	(12)	(17)	(12)	(23)	(19)	(20)	(103)
Inspector	2	2	3	4	2	1	14
	(56)	(81)	(102)	(91)	(72)	(44)	(447)
Labourer	1	1	2	9	7	5	25
	(16)	(8)	(17)	(42)	(74)	(53)	(210)
Storekeeper	1	1	4	7	8	2	23
	(8)	(7)	(13)	(38)	(31)	(25)	(122)
Miscellanous	24	21	15	14	13	4	91
	(121)	(217)	(302)	(286)	(167)	(136)	(1232)
Total	44	46	51	59	50	18	268
	(460)	(657)	(758)	(717)	(510)	(342)	(3444)

Table 2

Average Number of Accidents per Worker
During Four Year Period by Age Group and Job

Job	21–28	29–36	37–44	45–52	53–60	61+	Total
Electrician	0·059	0·021	0·111	0·222	0·125	0·000	0·080
Turner	0·107	0·020	0·063	0·069	0·100	0·000	0·058
Miller	0·045	0·015	0·077	0·152	0·071	0·000	0·060
Grinder	0·039	0·016	0·063	0·147	0·063	0·167	0·060
Fitter (skilled)	0·075	0·014	0·091	0·057	0·121	0·093	0·096
Fitter (semi-skilled)	0·083	0·177	0·167	0·087	0·210	0·050	0·126
Inspector	0·036	0·025	0·029	0·044	0·028	0·023	0·031
Labourer	0·063	0·125	0·118	0·214	0·095	0·094	0·119
Storekeeper	0·125	0·143	0·308	0·184	0·258	0·080	0·189
Miscellaneous	0·199	0·097	0·050	0·049	0·078	0·029	0·073
Total	0·096	0·070	0·067	0·082	0·098	0·053	0·078

Table 4 gives data from which the rankings of $(O-E)/E$ expressions and median ages of men employed on jobs were correlated. The rank order correlation coefficient obtained was 0·556. This is significant at the 5 per cent level.

Table 3

Observed (O) and Expected (E) Accidents by Age Group and Job

Job		21–28	29–36	37–44	45–52	53–60	61+	Total	Chi-squared
Electrician	O:	2	1	3	4	1	0	11	5·16*
	E:	3·32	3·36	1·85	1·51	0·80	0·16	11·00	
Turner	O:	3	1	3	2	1	0	10	0·23
	E:	2·04	2·72	2·45	1·82	0·75	0·21	9·99	
Miller	O:	3	1	4	5	1	0	14	5·15*
	E:	4·75	3·39	2·60	2·03	1·02	0·16	13·98	
Grinder	O:	2	1	4	5	1	1	14	4·86*
	E:	3·74	3·38	3·29	2·14	1·20	0·24	13·99	
Fitter (skilled)	O:	5	14	11	7	12	4	53	0·86
	E:	7·77	8·49	9·87	12·30	11·78	2·78	52·99	
Fitter (semi-skilled)	O:	1	3	2	2	4	1	13	0·23
	E:	1·88	1·95	1·32	3·09	3·04	1·73	13·01	
Inspector	O:	2	2	3	4	2	1	14	0·01
	E:	2·14	2·32	2·75	3·01	2·82	0·95	13·99	
Labourer	O:	1	1	2	9	7	5	25	0·17
	E:	2·29	0·84	1·70	5·16	10·81	4·21	25·01	
Storekeeper	O:	1	1	4	7	8	2	23	0·21
	E:	1·84	1·17	2·08	7·48	7·25	3·18	23·00	
Miscellaneous	O:	24	21	15	14	13	4	91	20·22†
	E:	11·17	14·62	19·59	22·78	15·77	7·13	91·06	

*$P=0·05$, †$P=0·001$.
In all cases, d.f. = 1.

Table 4

Observed (O) and Expected (E) Accidents in the Upper Age Groups of Jobs with Different Median Ages

Job	Median Age	Accidents in the 45+ Age Group		
		O	E	$O–E/E$
Electrician	35·28	5	2·47	+1·03
Turner	37·90	3	2·78	+0·08
Miller	35·44	6	3·21	+0·87
Grinder	37·50	7	3·58	+0·96
Fitter (skilled)	44·20	23	26·86	−0·14
Fitter (semi-skilled)	48·84	7	7·86	−0·11
Inspector	43·60	7	6·78	+0·03
Labourer	57·12	21	20·18	+0·04
Storekeeper	52·22	17	17·91	−0·05

§ 4. Discussion and Conclusions

On the basis of the results reported above, affirmative answers may be given to the two questions raised earlier. Accident rates in some jobs do appear to increase with age to a greater extent than in others, and the jobs in which high accident rates occur in the upper age groups seem, on the whole, to be those in which there is a preponderance of younger workers. The fact that the major discrepancies between observed and expected accident frequencies occur in the 45–52 years age group rather than in the 53-plus group suggests that selection occurs before the age of 52 is reached. Those in the 53-plus age group may either be doing somewhat less demanding work, although still within the same job category, or alternatively they may be atypical of their age group because many of their contemporaries have moved to other jobs. These possibilities require further examination.

The high value of chi-squared in the case of the Miscellaneous jobs is difficult to explain. It reflects *fewer* accidents than would be expected in the upper age groups of jobs occupying a group of workers whose median age is approximately two years higher than that of the firm's total. As the workers in the Miscellaneous group are distributed over some forty different jobs, it is impossible. however, to relate their age distribution to their accident behaviour.

The evidence presented in this article cannot, perhaps, be regarded as conclusive; the total number of accidents occurring in four years is not sufficient to warrant more than a tentative conclusion. However, the results provide a basis for the interpretation of previous, apparently equivocal results in this field. It seems that fluctuations with age of accident rates may well be a function of the type of work studied. The fact that older workers are seen to be particularly liable to accidents in jobs normally occupying mainly younger workers suggests strongly that they are not able to meet the demands of these jobs successfully, and may explain the fact that these jobs are ones in which older workers are only rarely to be found.

It is felt that this should not be taken as a reason for further limiting the employment of older workers on jobs in which their accident rate is high, but rather that an attempt should be made, by modifying the work, to minimize the demands which older workers are unable to meet.

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Il s'agit d'une investigation où on a etabli un rapport entre la fréquence des accidents d'une part et l'âge et le genre de travail de l'autre. La distribution des âges dans les accidents qui se sont produits pendant une espace de quatre ans chez des ouvriers dans chacune de neuf occupations a été comparée aux distributions auxquelles on se serait attendu étant donné que la différence de métier ne cause pas de différences dans la variabilité d'incidence des accidents selon l'âge. On a obtenu trois différences significatives entre les distributions (*a*) observées et (*b*) attendues. Elles se rapportent aux métiers d'Électricien, de Fraiseuse et de Repasseur qui sont tous des métiers où, en général, la plupart des employés sont jeunes. Les âges médians des employés dans neuf occupations sont corrélatifs aux mesures dans lesquelles les accidents chez les ouvriers plus âgés sont plus ou moins nombreux que ceux qui étaient prévus. Cette corrélation est significative, et elle indique que les accidents arrivant aux ouvriers plus âgés dans les métiers qui emploient d'ordinaire des ouvriers plus jeunes tendent à dépasser le chiffre anticipé. On en vient à la conclusion que la variabilité de la fréquence des accidents suivant l'âge dépend du genre de travail étudié. On croit que les resultats de cette investigation démontrent les difficultés que présentent, pour les ouvriers plus âgés, les conditions de certains métiers.

Im vorliegenden Aufsatz werden die Verhältniszahlen von Arbeitsunfällen mit Alter und Arbeitsarten verglichen. Die Altersverteilung von tätsachlichen Arbeitsunfällen im Verlauf von vier Jahren bei manuellen Arbeitern in neun Erzeugungsbranchen werden verglichen mit der Arbeitsverteilung die zu erwarten wäre bei der Annahme, dass die Verschiedenartigkeit der Arbeitsstellen keinen Einfluss auf die durch Alter bedingten Fluktuationsunterschiede in Unfällen hat. Die Untersuchung hat drei wesentliche Unterschiede zwischen der festgestellten und der erwarteten Verteilung ergeben. Diese Unterschiede beziehen sich hier auf Elktriker, Müllereiarbeiter und Metallschleifer, alles Berufe, in denen normalerweise jüngere Kräfte verwendet werden. Die Mittelwerte der Altersstufen von Arbeitern in neun Arbeitsstellen stehen in Korrelation gebracht mit dem Vorkommen von Arbeitsunfällen in höheren Altersstufen, in denen Unfällen öfter oder seltener als erwartet wird vorkommen. Diese Korrelation ist bezeichnend, und sie zeigt an, dass ältere Arbeiter, beschäftigt auf den normalerweise von jüngeren Kräften bekleideten Arbeitsstellen, die Tendenz zu häufigeren Unfällen zeigen, als erwartet wird. Daraus

wird gefolgert, dass die durch das Alter bedingte Fluktuation in den Verhältniszahlen von Unfällen eine Funktion der untersuchten Arbeitsarten ist. Das Resultat der Untersuchung deutet auf die Schwierigkeiten hin, die ältere Arbeiter bei der Erfüllung von Ansprüchen haben, die gewisse Arbeitsarten stellen.

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HUMAN ERRORS AND TRANSPORT ACCIDENTS

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The paper discusses the part played by three psychological processes, here called ‘ the false hypothesis ’, ‘ pre-occupation ’ and ‘ emergency mechanisms ’, in the causation of transport accidents. Some of the experiments in which these processes have been studied in the laboratory are described. Explanations of the errors responsible for certain train collisions, when the driver had passed one or more signals at danger, and for certain aircraft accidents are suggested by reference to one or other of these processes.

§ 1. Introduction

Can laboratory experiments throw any light on the errors responsible for transport accidents ? Do the psychological processes revealed in laboratory experiments play a part in the causation of accidents ? Do the experiments suggest any hypotheses that deserve serious consideration ?

This paper is a commentary on these questions. Three psychological processes out of which errors may arise are discussed and some of the experiments in which they have been studied are described. These processes have been chosen for discussion mainly because they appear to be especially relevant, but also because they are of interest from a psychological point of view. Tentative hypotheses are formulated and the attempt made to show that they can provide explanations of certain accidents which have been chosen as examples. These explanations appear possible, on the facts known to the writer. No claim is made, however, that they are proved, or that they necessarily apply to all similar accidents.

The examples fall into two classes : railway accidents occurring after a driver had passed one or more signals at danger, and accidents to civil aircraft. They have been chosen for several reasons. They were all subjected to expert and thorough official enquiries, the reports of which have been published and are readily available. The reports contain reasonably sound evidence to show what the driver or pilot did wrong, and that his error was the main cause of the accident. Although in some cases the circumstances were unusual, they were not so unusual as to explain the error. In every case the driver or pilot was highly trained, experienced and of good repute. He was in good health, and he was not under the influence of alcohol or drugs. No other classes of accident appear to serve the purpose of this paper so well, although no doubt other examples could have been taken.

In some cases the official report goes no further than to say that an error was made and was responsible for the accident, and does not embark on any psychological discussion of the nature of the error or the reasons for it. In other cases it attributes the error to such things as “ lack of concentration ”, “ inattention ”, “ failure of judgment ” or “ fatigue ”. Explanations in terms such as these are, however, unsatisfactory because either they do no more than give a name to what has obviously occurred, or they suggest a cause without giving any insight into the way in which it might have operated to produce the accident in question. For more precise psychological explanation we need to consider more immediate and detailed causes. Fortunately it is upon these that experimental studies seem most able to help.

§ 2. THE FALSE HYPOTHESIS

We shall discuss first a process we may call 'the false hypothesis', which results from the fact that people respond to situations as they conceive them to be, and this may be very different from what they really are.

One of Bartlett's simple experiments will serve as an illustration (1932, p. 26). Expose for a brief period a picture in which can be seen a solid-looking wall, a closed five-bar gate and on the far side of the wall a notice-board on which there is something written. Ask what is written, and many subjects will reply confidently: 'Trespassers will be prosecuted', although they cannot in fact read the words. Or again, expose briefly a crude drawing of an aircraft under which appears the word 'airoplaxe', and ask what is written. Many subjects will reply 'aeroplane'. These experiments, with many others, show that one tends to perceive what one expects to perceive. In these instances, what one expects is immediately determined by the other components of the picture, that is, by the setting in which the words are presented, the wall and the gate in the first instance, and the aircraft in the second. In other cases what is seen may be determined by the observer's previous experience, recent and remote, or by suggestions given in the experimenter's instructions.

Let us now consider a similar although more elaborate experiment. The subject is presented with groups of words like 'Trespassers will be prosecuted' in different settings, in the appropriate setting of wall, gate and notice-board, for instance, or by themselves in a neutral setting, or in an *in*appropriate setting, say, on a sign-board in a drawing of a pub. The words will be rendered correctly with short or very short exposures when the setting is appropriate, at somewhat longer exposures when the setting is neutral. When the setting is inappropriate, errors will be frequent with short exposures, and the words will only be rendered correctly with relatively very long exposures, or if perception is made easier by printing the words in large lettering. In this experiment the subjects' expectations are mainly the product of the setting. Similar results are obtained when the expectations have been created by previous experiences.

The reader may question whether the correct rendering of the words depends upon the efficiency of perception or of inference or guessing. Nothing is to be gained, however, by making such distinctions here. They are not made by the subjects, who tend to accept the veridicality of what they report as present in the pictures. When the words on the notice-board by the wall and gate are, say, 'Refreshments will be provided', and not 'Trespassers will be prosecuted', the latter words tend to be reported when the exposure has been short. If subjects are then told that they have made an error, and are given a second trial, they often show irritation and when they have perceived the words correctly, reproach the experimenter for misleading them.

It is usual for a person to have expectations, or to hold to what may be called an hypothesis, about every situation he meets, even when information is notably incomplete. This hypothesis, which is in some degree the product of his previous experience of similar situations, governs the way in which he perceives the situation and the way in which he organizes the perceptual material available to him. As he receives further information, his hypothesis tends to be modified or amended or abandoned and replaced. Sometimes, however, an hypothesis, and the expectations which go with it, appear to be unduly resistant to change. At the extreme in this respect are delusions : a deluded person shows in some matters a flagrant disregard for obvious facts.

A further experiment illustrates the effect of increasing information (Davis and Cullen 1958). Project a picture on to a screen, starting with an illumination too low for any of its details to be discerned. Now increase the illumination slightly so that there is a pattern of light and shade on the screen. At this point most subjects will try to make some sense of what they see and impose meaning on it. One subject may ‘ see ’ the material as a horse or a rabbit, another as a man, and another as trees. Each of these identifications is the result of an hypothesis, which is either amended or discarded and replaced as the illumination is increased and further information becomes available. With the pictures and conditions used in one such experiment, normal subjects produced and discarded in turn some five or six hypotheses before the illumination had been increased sufficiently for them to make out what the picture really showed. These were false hypotheses which only persisted so long as some details were misinterpreted and others neglected. They were discarded when details were perceived which made them untenable.

Anxiety frequently enhances the tendency to form hypotheses. When anxiety is at a low level, a person is able to tolerate uncertainty in a situation about which information is incomplete and to wait patiently for more information before adopting an hypothesis and initiating action. If anxiety is aroused, on the other hand, he tends to adopt an hypothesis prematurely, and thus runs a substantial risk that it is false. Walking along a lonely road at night, for instance, one may be content not to impose meaning on patterns of light and shade, but if one is anxious one may begin to see lurking marauders and perhaps even act impulsively in consequence.

At the extreme are the hallucinations experienced in some circumstances when a person has a strong expectation of danger. Keenly aware of the dangers of an obstruction on the road, for instance, a motor-vehicle driver may hallucinate another vehicle or cattle or road block. Most drivers have experienced such hallucinations at some time or other. They occur occasionally when one has been driving at night for a long distance, perhaps in difficult conditions, usually when attention is beginning to fail. When one is fresh and alert, one's perceptions serve to reassure that the road ahead is clear. As one tires this reassurance fails, and mildly frightening hallucinations occur when attention lapses momentarily. What one then hallucinates depends upon what kinds of danger one anticipates : one person may, for example, be expecting cattle on the road, another trucks without lights.

Subjects who are anxious, either because they suffer from clinical anxiety states or because they have been made anxious during an experiment, as can readily be done in various ways, behave differently from normal subjects when presented with pictures at low illumination. In particular, they produce significantly more false identifications : where a normal subject produces five or six, an anxious subject produces fifteen or twenty, or even more. Indeed, their perceptions undergo frequent and rapid reorganization and have, so to speak, a kaleidoscopic character. Their performance is thus erratic and inconsistent, but as no one identification remains for long, they do not make the mistake seen in some other circumstances of persistently neglecting certain details which happen to be discrepant to their hypothesis.

There are several conditions under which subjects tend to show the opposite behaviour, of holding on to a false hypothesis. One such condition is when there is insufficient information to show the hypothesis to be false, as, for example, when in an experiment the illumination is too low. Another factor probably lies in the personal characteristics of the subject, some people tending to be consistently more ' rigid ' than others. There are, however, five conditions favouring the persistence of false hypotheses which seem especially likely to cause accidents in certain circumstances.

(*a*) A subject tends to hold to a false hypothesis when his anxiety level is low, and perhaps especially when a relatively high level of anxiety has recently been reduced. A special example of this tendency is seen in what Drew called the ' specific end deterioration ' (*vide* Davis 1948), which occurs towards the end of an arduous task when the more obvious difficulties and dangers have passed. When the end is in sight, the subject may feel that he is ' as good as home ' and relax his attention.

An accident which looks very much like an illustration of this tendency is the *Harrow and Wealdstone train collision* (8*th October*, 1952). The driver of a train from Perth passed the colour light distant signals at caution and two semaphore signals at danger without reducing speed. There seems no doubt that all these signals were clearly visible although there was some patchy fog ; the colour light distant signal, which was strong and well sited and focused, was probably visible for at least four seconds. It could only be concluded that the driver, " an engineman of considerable experience and mature age with a good record", . . . " must have relaxed his concentration on the signals for some unexplained reason ". This relaxation must have lasted for more than a minute.

He had brought the train from Crewe, which he had left half-an-hour late. He had lost time all the way, for there had been continuous fog, and conditions had been very difficult. He had been stopped for two minutes at Watford Tunnel North End and had then strictly observed the subsequent speed restriction in the tunnel. He had then got up to normal speed again, i.e. 50–60 m.p.h. The fog was thinning, and the sun was coming up. He was coasting, on the falling gradient, with the regulator closed, as was the custom, when he passed the signals.

It may be supposed that he was not on the alert for the signals because he was expecting an easy and uninterrupted run in to Euston, and that he had this optimistic expectation, not fully justified by ordinary experience on the route and in the event false, because, after a long period of strain, his difficulties were easing and he saw that he was coming to the end of an arduous journey.

The error responsible for the *Betley Road train collision* (17*th November*, 1954) might be explained similarly. The driver of a freight train ran past a colour light signal at Red, after passing the distant at Yellow, without reducing speed. The train was 95 minutes late, as a result of numerous checks, and because there had been dense fog. The accident occurred about five miles from Crewe, where his duty would have ended. The fireman was engaged in cleaning up the foot-plate in preparation for leaving the engine.

(*b*) The conditions under which an engine driver, or pilot or other operator, perceives a signal are usually such that he has a strong expectation of what he will perceive, this expectation being derived perhaps from a lengthy experience of similar situations and an appraisal of the current situation which is usually both confident and correct. Sometimes he is on the alert for departures from what he would normally expect. If he is not, he may fail to look out for, or fail to perceive correctly, a signal of considerable clarity in terms of strength or duration. Thus he may totally neglect a signal which he does not expect, or misread a signal if what it indicates is contrary to what he expects. He then makes an error because his appraisal or conception of the situation and its probabilities is false.

Two further examples of railway accidents appear to illustrate this point.

The Ludlow train collision (6*th September*, 1956). That the driver's error was due to a false hypothesis is suggested by the official report. He ran past a distant signal at caution and two stop signals at danger without reducing speed. " The accident took place at a period of the 24 hours when vitality is at its ebb, and this may have led to " the driver's " lack of concentration. . . . He may also have been lulled to some extent, through his long knowledge of the working over the line, by the expectation of a clear run through Ludlow as is usual with this train."

It is only fair to add that there was another factor in this case. The engine was equipped with Automatic-Train-Control apparatus, but the siren failed because it was jammed by a thread of cotton waste.

The Lewisham train collision (4*th December*, 1957). The error responsible for this accident appears to have a similar explanation. In fog the driver passed a Red signal after two warnings, about a quarter mile apart, of a Double Yellow and a Yellow. In evidence at his trial he remarked that he had expected a Green signal at St. John's " because I have never been stopped there in the whole time I have been travelling ".

(*c*) An hypothesis also tends to be adhered to if it serves as a ' defence ', that is to say, if it relieves anxiety, however unrealistically it does so. This is the reason why delusions persist in the mentally ill, and also why scientists sometimes hold to a hypothesis long after it has appeared to others who are less personally involved to have been disproved. Similarly, a person in grave danger sometimes holds to a comforting hypothesis about his situation despite clear evidence of its falsity. Probably this accounts for some instances in which a pilot in serious danger has persisted in an inappropriate course of action as if unaware of his danger. Of the same kind are the comforting misinterpretations of symptoms to which patients suffering from a mortal illness are prone.

(*d*) A further situation which seems to favour the persistence of false hypotheses is that where several different parts or ' components ' of a task make demands upon the subject and require his attention. If one component gains dominance because it needs or seems to need special attention in order, for example, to avert an imminent danger, he tends to simplify his task by accepting hypotheses about other components relatively uncritically. In other words, hypotheses about components of a situation which have become of subsidiary importance tend to be corrected less readily when new information becomes available. This tendency will be discussed further in the next section.

(*e*) Similarly, a driver or pilot who holds a false hypothesis about the part of his equipment on which he is concentrating may fail to notice or may misread signals from other parts which do not fit the hypothesis and may thus cut himself off from the very data by which he might be corrected. Two examples may be quoted of accidents for which errors of this kind appear to have been responsible.

The Avro accident in the Solent (*6th August*, 1955). The starboard engine began to surge and lose power. The pilot reported to Traffic Control that the engine was running roughly and that the propellor constant-speed unit had failed. He tried to clear the surging by operating the throttle and pitch levers through their full range but without effect. He did not feather the propellor. He opened up the port engine to full power, but the aircraft continued to lose height. Shortly afterwards the port engine also lost power, and he ditched the aircraft. Examination of the wreckage gave no evidence of pre-crash damage or mechanical failure, but showed that the fuel tanks were empty. Having erroneously concluded that the propellor constant-speed unit was defective, the pilot did not carry out a thorough cockpit check.

The Viscount accident at Blackbushe (*20th January*, 1956). An experienced instructor intended to feather the No. 4 propeller in order to simulate No. 4 engine failure, but moved No. 3 H.P. cock lever instead of No. 4. He then throttled back No. 4 engine as intended, thereby losing power from both starboard engines at a critical point of the take-off. In confirming his actions he glanced at the gauges showing r.p.m. and torquemeter pressure for No. 4 engine, both of which he read as showing zero. The small pointer of the r.p.m. gauge would have indicated 10 000.

It is not easy to prove that these or other similar accidents were due to the psychological process which I have described as that of the false hypothesis. Some evidence in corroboration comes, however, from the statements made by the drivers and pilots about their state of mind when they made the error. In the cases of the Harrow and Wealdstone and Betley Road collisions the drivers did not survive. In the other cases their statements showed that their appraisal of the situation had been wrong, and are compatible with the explanation that their errors arose out of their wrong appraisals.

2.1. *Implications for Methods of Presenting Information*

The experimental evidence points to the conclusion that if a signal is to be perceived correctly its strength or duration, or insistence, has to be much greater when it is contrary to expectation than when it conforms to it. This conclusion may require some qualification, but it is broadly valid. It applies to auditory perception as well as to visual perception. The effect of a false expectation may be a large one in laboratory experiments, even when the tests are made on sophisticated subjects who are not unprepared for attempts to mislead them.

This conclusion is of some importance because in many investigations which have set out to establish the strength or duration, or character, of a signal required for it to be detected and interpreted reliably, the signal has been presented either in a neutral setting in which expectation is minimal or in a setting in which it conforms broadly to what is expected. The experimenter's instructions usually establish appropriate expectations and prepare the subject for what he is to perceive. Outside the laboratory, however, many of the most crucial signals are those which are contrary to reasonable expectations.

An error with serious consequences may be made because a signal is not noticed or is misread, and may then be attributed to the insufficient strength or duration of the signal. However, errors of this kind are not always prevented by increasing the strength and duration of the signal or by reinforcing it with further signals. Thus even the signals of Automatic-Train-Control systems have occasionally been neglected. People may fail to see what stares them in the face if their looking is guided by a false hypothesis. It is perhaps more profitable to consider such errors as being due to the persistent holding to a false hypothesis despite the evidence to the contrary which the signal provides. The practical problem is then seen in a different perspective, but is still : how should the necessary information be imparted ?

§ 3. PREOCCUPATION

In some war-time experiments with an artificial aircraft cockpit (Davis 1948), one of the effects of the increasing anxiety which the tests evoked in subjects was to produce a degree of perceptual disorganization. When anxiety was at a low level at the beginning of a test, the subject tended to respond to the instrument panel as an integrated whole. As his anxiety increased, the several components of his task tended to become disarticulated. His attention then tended to be directed more and more to the particular component of the task which had gained a special importance. He became preoccupied with this component, which was singled out, at the cost of neglecting other components which had not acquired the same degree of urgency. It appeared that when anxiety in relation to one source of danger increased, attention to other less urgent matters declined ; in this way the subject simplified his task. He might then fail to perceive and respond to signals which were peripheral, objectively or subjectively, to the matters preoccupying him. Trying hard not to spill the over-full cup of tea one is carrying, one trips over the dog!

The way in which this process might enter into errors responsible for aircraft accidents is illustrated by the following extracts from accident reports (Davis 1948, p. 36) : " lost sight of the leading aircraft while calling on the R.T. He pushed the control column forward and hit the propeller of the leading aircraft with the rudder ". " While calling on the R.T., collided with a tractor, one foot off the perimeter." " Did not correct a swing on take-off adequately, probably because his attention was distracted by the red-light for the starboard inner engine."

The Argonaut accident near Idris Airport (*21st September*, 1955). ". . . having made three unsuccessful attempts to line-up and land on runway 11, the pilot " on his fourth attempt " allowed his desire to keep the runway lights in view to affect his judgment, in that during a visual approach to the runway he failed to make adequate reference to his flight instruments." " Unknowingly he permitted the aircraft to descend below its correct approach path."

In all these examples the error responsible for the accident was one of neglect, due to preoccupation with another matter which had acquired a degree of urgency.

There are wide differences between individuals in the degree to which they tend to become preoccupied with one aspect of a situation to the exclusion of attention to other aspects. The state of mind is akin to that which is popularly called ' absent-mindedness '. The tendency is especially strong in those of obsessional personality, who tend to be keen, conscientious and efficient in most respects.

§ 4. EMERGENCY MECHANISMS

Man like other animals is equipped with so-called ' emergency ' mechanisms. When dangers, whether physical or psychological, appear imminent, the ' drives ' underlying behaviour become stronger and behaviour undergoes certain characteristic changes. In particular, responses are more readily elicited ; that is to say they are elicited by less intense and less specific stimuli. They tend to be more forceful, more extensive and more rapid. At the same time they tend to be less regular, less organized and less coordinated. The emergency mechanisms thus enable the subject to react rapidly and vigorously to situations which threaten him and facilitate the overcoming of obstacles of certain kinds. They are of biological value for this reason, but their effects on behaviour are not always advantageous, for many of the danger situations which human adults meet require not vigorous activity but restrained, deliberate and accurate responses. When this is so, as it usually is in the case of pilots or others who are in control of complicated machines, the emergency mechanisms impair efficiency. A vicious circle may then be instituted, for, efficiency being impaired, the danger tends to become more imminent, and there is then a further decline in efficiency. The typical sequence is seen in a panic, when a sudden alarm leads to hasty and excessive measures which add to the cause for alarm.

Normally a person reacts to an untoward incident in a way which his previous training and experience have taught him is likely to be effective. The incident may then have no significant consequences. However, if he is caught unawares, or if he is susceptible for some other reason, or if his initial responses have proved ineffective in removing the danger, the emergency mechanisms may come into play. This may occur very quickly, within a matter of seconds. He may then add to his difficulties by responding excessively and inappropriately. Having done so, his behaviour may undergo a rapid and progressive disorganization. Anxiety may add to his difficulties by causing the hypotheses which guide him to change quickly and make his actions vacillating and poorly sustained. Once instituted, the vicious circle is likely to end in disaster.

Breakdowns of this kind were observed in the artificial cockpit experiments already mentioned and the emergency mechanisms upon which they depend have been studied in numerous experiments (Davis 1957). They appear likely to have been responsible for some aircraft accidents, such as the one now to be described.

The Italian Airlines accident near Idlewild Airport (18*th December*, 1954). The accident occurred during the fourth instrument approach to the airport in reduced visibility. The aircraft was under radar observation throughout. At about four miles from the touch-down point it descended below the lower limit of the glide-path and continued to descend despite repeated warnings by the radar controller. Having come down below the overcast to about 200 feet, it pulled up sharply and climbed back into the overcast. It then made a second descent to a low altitude, pulling up sharply again and climbing to the centre glide-path. On a third steep descent it struck a pier just inside the middle marker and about $\frac{3}{4}$ mile from the touch-down point.

It seems probable that the pilot was trying to come in under the weather, descending below the overcast in an attempt to proceed visually to the runway. This procedure might have had some advantages, although it was not in accord with good operating practice and was contrary to the advice given from the ground. Whatever the intention, the manoeuvres were poorly executed, and there was evidence of vacillation and ' abrupt control action ', so abrupt at one point that galley equipment spilled down the cabin aisle. After the first descent the manoeuvres appear to have become sharper and less regular, the pilot's behaviour undergoing rapid disorganization, with his responses growing more and more excessive and hasty and less and less appropriate.

The official report concluded that " a contributing factor . . . was pilot fatigue due to the particular and difficult circumstances " and subscribed to the " belief that the pilot's efficiency and normal ability were seriously impaired by fatigue ". It did not say clearly to what process the term ' fatigue ' refers. However, it stated that fatigue " was not only present as a result of the time en route, approximately $22\frac{1}{2}$ hours, but mostly as a result of the additional extended $2\frac{1}{2}$ hour period devoted to the four approaches and the high mental and physical demands made upon the pilots ". Yet the Atlantic crossing had been uneventful, and the aircraft had landed at Gander and Boston without difficulty. The crew included four experienced pilots, and " there is no reason to believe that normal rest procedures were not followed ". In any event, fatigue hardly accounts for the severe deterioration in the pilot's performance, amounting to a gross disorder of elementary flying skill.

In this case, as in the others cited above, the official enquiry made a very careful study of the engineering and operational aspects of the accident. It gave far less detailed and far less informed consideration to the psychological aspects. A more precise definition of the psychological factors would have been difficult, but not necessarily more difficult than was the examination of the wreckage for mechanical faults. Closer study of the psychological factors in such cases would indeed be valuable because were more known about them and their manifestations, traffic controllers might be able to give more effective help and advice than they were able to do on this occasion.

I am greatly indebted to Dr. W. E. Hick for his encouragement and help in the preparation of this paper, and in particular for drawing my attention to the Idlewild accident. I have borrowed many suggestions from him, but I must take full responsibility for the views expressed.

Il s'agit du rôle joué, parmi les causes des accidents de transport, par trois procédés psychologiques, qu'on appelle ici ' la fausse hypothèse ' ,' la préoccupation ' et ' les mécanismes de crise '. Quelquesunes des expériences dans lesquelles on a étudiés ces procédés au laboratoire sont décrites. On explique les erreurs qui ont mené à certaines collisions de chemin de fer, quand le conducteur avait dépassé un ou plus d'un arrêt, et à certains accidents d'aviation, en s'appuyant sur l'un ou l'autre de ces procédés.

Diese Arbeit befasst sich mit der Frage, in welchem Umfang 3 verschiedene psychologische Prozesse, hier ' falsche Hypothese ', ' Voreingenommensein ' und ' Notfall-Reaktionen ' genannt, Verkehrsunfälle mit-verursachen. Einige diesbezügliche Experimente werden beschrieben. Es wird versucht, den einen oder anderen der 3 genannten psychologischen Prozesse zur Erklärung bestimmter Eisenbahnunfälle (bei denen ein oder mehrere Not-Signale überfahren wurden) und Flugunfälle heranzuziehen,

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SENSORI-MOTOR PERFORMANCE UNDER VARYING NOISE CONDITIONS

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A group of subjects performed a task in quiet and noisy environments. The noise was intermittent, within the frequency range of 75 to 9600 cycles and at sound levels of 70, 80, 90, and 100 db. The study was experimental, but simulated an occupational situation.

There was a tendency for more errors and less precision when working in the noisy environment. Response times were slower and the number of errors greater than when noise levels and frequencies were highest. The frequency range of 2400–4800 cycles was associated with the slowest response time and largest number of errors, both at 90 and 100 db.

It appears that intermittent noise may have a reducing effect on the individual's capacity for quick and precise execution of coordinated movements. The implications for safety and certain production tasks seem obvious.

When considering the effect of noise on people, its possible hazardous influences have major significance. There is ample clinical and experimental evidence that excessive sound pressures can injure the ear or induce an accident when an alarm or warning signal is masked by a louder sound. Noise may also have another bearing on safety: the question occurs, "Can noise affect safe performance?" The extent of this possibility is a function of the closeness of the relationship between noise and mental and motor activity—as well as the implications such a relationship may have for performing tasks safely.

A number of investigations have been reported on this relationship, but most have been concerned with steady-state noise. In a large number of environmental situations noises are neither steady nor expected. Intermittent noises, therefore, would appear to be of significant interest. Also, earlier investigators generally have not chosen to consider the frequency of the sound pressure waves as well as their intensity, and the relation of these factors to behaviour. The purpose of this experiment was to probe these relationships.

§ 1. Method

Since environmental conditions other than noise might have an influence on performance, and because many previous studies may be criticized for their lack of controls, it was decided to limit the investigation to the following conditions:

(1) Relative humidity—between 30 per cent and 70 per cent.

(2) Temperature—maintained at approximately 70°F. A relationship between temperature and accident rate has been reported, indicating that in the case of factory workers, when the temperature is above 75° or below 65°F the accident rate rises (Osborn and Vernon 1922).

(3) Illumination—artificial, unvarying for each subject and meeting the American Standard Practice for Industrial Lighting Requirements for fine bench and machine work.

(4) Time—between the hours of 9.00 a.m. and 5.00 p.m., the normal work period.

(5) Subjects—chosen according to the following requirements :

(*a*) Age—18 to 35 years, the approximate age group possessing the shortest reaction time (Bellis 1933).

(*b*) Hearing—normal as determined by audiometric measurement according to the standards of the American Medical Association (Council on Physical Medicine 1945).

(*c*) Vision—near vision acuity of 14/14 to 14/21 for each eye, as determined by the Snellen Chart, considered essential for precision work (Bridges 1946).

(*d*) Food—no subject was chosen if he had over-indulged in eating within the past three hours. The digestive organs, when taxed require an extra supply of blood which may be drawn from other less active organs (Kimber and Stackpole 1936). This is suspected as the cause of the ‘ loggy ’ feeling following the eating of a heavy meal. Within three hours, however, the stomach can be expected to be emptied and this condition relieved (Crandall 1935).

(*e*) Alcohol—no subject was allowed to take alcohol within at least three hours prior to participating in the experiment. It has been shown that alcohol in even small amounts impairs hand–eye coordination (Tufts College, 1951).

(*f*) Fatigue, debilitation etc.—no subject was chosen if he stated, when asked, that he felt in any way ‘ under par ’ and so not up to his usual physical and mental capacities.

(*g*) Sleep—although the normal sleep ration leaves a large safety factor over and above actual needs, so that a moderate reduction in hours of sleep has no apparent effect (Anon. 1951), some indications have been obtained that deterioration in performance may occur (Husband 1935). It was considered advisable, therefore, to select only subjects who stated they had their regular amount of sleep for the past 48 hours.

Such factors as learning, experience, capacity and status were controlled by the preliminary testing and re-testing of each subject until a plateau for his scores was achieved.

Noise reproduction

The noise source was a battery of series connected audio-oscillators, each consisting of a resistance-tuned oscillator in combination with an output meter and attenuator. By proper notation of the instruments and meter settings each of the sounds could be duplicated as desired. Narrow band (not pure tone) noises were chosen in the octave bands 75–150, 150–300, 300–600, 600–1200, 1200–2400, 2400–4800, 4800–9600 cycles per second. Each noise was expressed at 70, 80, 90 and 100 db*.

The noises were recorded on magnetic tape, using a recorder which was laboratory checked and found to have characteristics satisfactory for the purposes of the study.

It was considered undesirable to have a consistently orderly progression of noises of either increasing or decreasing frequency or intensity. Also it was believed that a single exposure to each noise would not give as reliable results as would a random repetition of the noises.

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* Here and throughout this report the decibel (db) referred to is 0·0002 microbar.

The random presentation was complicated by the number of individual noises to be used—a total of 28—and the possibility of fatiguing the subjects since it was intended that they be tested both in noise and also in quiet to obtain comparative results. It was decided, therefore, to run the experiment so that each subject would perform in noise for no more than 30 minutes and in quiet for the same period. A three-minute interruption, midway between each period, was provided as a rest spell.

Each noise was recorded three times for periods ranging from 10 to 23 seconds. The sum of the three periods equalled 45 seconds in each case. Intermittency was accomplished in the recording by inserting brief (2 to 13 seconds) intervals of quiet between each variety of noise.

The recording began with the spoken word ‘ Go ! ’. This was the starting signal for which each subject was instructed to be alert. The tape was then blank (quiet) for 10 seconds after which the first noise was presented. The recording of the random presentation of noise and quiet intervals proceeded until 777 seconds (12·95 minutes) had elapsed. Then the following sentence was recorded, ‘ Stop now and rest until instructed further ’. Quiet followed for 165 seconds and then the recorded announcement, ‘ Get ready to start again in 10 seconds ; 9, 8, 7, 6, 5, 4, 3, 2, 1, Go ! ’. The word ‘ Go ’ occurred 180 seconds after the rest spell began. The recording of the noises continued for another 773 seconds. The total time of the recording was 1730 seconds (28·83 minutes).

The experimental task and its equipment

The experimental task employed an adaptation of a compound slide rest, comparable to the type found on engine lathes. The apparatus consisted of a stylus mounted over a platform in which was embedded an electrically conductive, irregularly shaped pattern resembling a ‘ key-hole ’ in outline. The pattern was set flush with the top surface of the platform. The stylus was mounted so that it could be moved in any desired horizontal direction by turning two handles, at right angles to each other, operating two screws which drove the stylus. The arm to which the stylus was attached was extended to accommodate a ball-point pen attachment, arranged so that a simultaneous record was made on paper of the path traced by the stylus. The conductive pattern was wired for connections with electrical recording devices.

Subjects were required to guide the stylus continuously around the pattern, using the handle controls, completing as many turns as they could within the time allowed. Breaking the contact between the stylus and the pattern interrupted the electrical circuit and actuated a system of electrical relays which in turn operated a timer, counter and permanent marking recorder. The break of contact also extinguished a flashlight-type lamp bulb, indicating incorrect operation. Thus a definite visual signal was presented, in addition to the subject's witnessing his error when allowing the stylus to deviate from the pattern.

When an error occurred, the subject was required to return the stylus to the pattern as rapidly as possible. This requirement of concentration, prompt detection and swift correction of an error may be considered typical of certain psycho-physical demands for accident prevention and efficient machine operation.

The apparatus was mounted on bench legs, approximating the height of the compound slide rest on an engine lathe. The subject was provided with a shop-type stool so that he could either stand or sit during the performance of the task.

The room in which the tests were conducted was on the 12th floor of a steel and concrete office building and possessed relatively low resonant properties ; the ceiling had been treated with acoustic tile ; the floor was completely carpeted and approximately 10 per cent of the wall surface was covered with heavy drapery material. The overall noise level in the room was 37 db which was created mostly by the passage of air through the ventilator grills employed in the air conditioning system ; this was the quiet condition for the study.

Collecting the data

The following data were taken :

(1) *Errors* (deviations from the pattern). A monitoring recorder which marked an electro-sensitive paper tape as the circuit was interrupted, was used to tabulate the errors. The instrument was capable of recording electrical impulses having a duration in the order of microseconds.

(2) *Response time* (the amount of time elapsing between the instant when the stylus broke contact with the pattern and its return). These data were taken from the paper tape which also showed the number of errors. The tape was wound continuously on a spool driven by a synchronous motor whose RPM was known. It was possible, therefore, to determine the response time by measuring the length of the marks on the tape.

(3) *Production* (the number of turns of the stylus around the pattern). The perimeter of the pattern was spaced into 100 equal divisions. This permitted a relatively accurate determination of the fractions of turns negotiated by the stylus at the end of each period of performance.

Conducting the experiment

Some subjects were engineers and workers experienced in operating a compound slide rest as a production tool, but the majority were clerical employees ; there were twice as many women as men. To ensure, as far as possible, that they consistently tried their best, a schedule of cash awards was announced as follows : For best score, $25.00 ; second and third best, $10.00 each ; fourth and fifth, $5.00 each. All other participants received $1.00. It was recognized that providing a monetary incentive might mean that subjects worked only because of an interest in the money. This was considered to be of little significance, however, in comparison to the desirability of providing a realistic motive. The scores of the participants, when determining the five top awards, were computed by averaging the data obtained for each subject during the ‘ quiet ’ and ‘ noise ’ phases of the experiment, then substituting the averages in a formula taking account of all three measures and of an overall ‘ precision rating ’ made by two assessors using a prepared scale in terms of which they judged the recorded tracks made during the experiment.

Each participant, before beginning the experiment, was asked to read a written set of instructions and was then permitted to perform the task for a 10-minute practice period. It was recognized that learning, through practice, would affect the results. Each participant was therefore given a series of 10-minute tests under ‘ quiet ’ conditions and the performance data were collected for each. Between each test and the next the subject was permitted to rest for five minutes. When three successive tests produced data varying within ± 5 per cent for each measure it was considered that the participant had reached a ‘ plateau of learning ’. He was then allowed 10 minutes rest before performing the experimental task.

He began the experimental task with either the quiet or the noise conditions for the first half of the test. After a 10-minute rest he repeated the test, but this time was exposed to noise if he had started with quiet or quiet if he had started in noise. Alternate subjects started under noise and quiet conditions. Thus a check was possible later for determining whether any variation occurred, such as would be attributable to fatigue or learning through practice.

It was necessary to reject many subjects following their completion of the experiment, when it was learned that mechanical interruptions in the experimental equipment or other uncontrolled disturbing factors had occurred. As a consequence, the sample group consisted of 30 subjects who started with noise and 22 who started with quiet.

§ 2. Results

Measures for the experiment as a whole

These are set out in Table 1, from which it can be seen that, on average, performance was poorer in the noisy conditions than in the quiet in terms of each of the three measures. The difference in number of errors was small and not significant, but the differences in response time and productivity were substantial. Scores for the individual subjects are set out in the Appendix. Taking errors and productivity together, it was found that 61 per cent of the subjects made more *errors per ‘ turn ’* in noisy than in quiet conditions.

Table 1

Overall Differences per subject of Performance between Quiet and Noisy Conditions

	Errors		Total response times (in minutes)		Productivity scores	
	Quiet	Noise	Quiet	Noise	Quiet	Noise
Mean	207	227	1·95	2·59	22·89	21·85
Median	178	213	1·27	1·87	22·08	22·02
Standard deviation	159	159	1·95	2·24	9·46	9·10
Mean difference	20		0·64		1·04	
Standard error of mean difference	7·15		0·28		1·26	
t	2·8		2·54		1·41	
$P <$	0·01		0·02		0·5	
Rank correlation coefficient between individual scores in noise and quiet	0·95		0·55		0·84	

The rank-order correlations between the scores of individual subjects in noise and quiet were high for errors and productivity, but lower for response times. Presumably the noise affected the response times of some subjects relatively more than others.

Neither group showed in any of the scores a change between the first and second halves of the experiment sufficient to reverse its position with respect to the other group. This indicates that fatigue and learning as between the two halves either did not affect the results to any substantial extent, or, if they did, their affects cancelled each other.

Relation of response time and errors to sound level and frequency range

The average response times and average numbers of errors were found for each of the experiment's 28 varieties of noise conditions and were then compared with the overall means for all noise conditions taken together. The averages of the varieties which exceeded these overall means are set out in Table 2.

Table 2

Response Time and Error Averages for Noise Variations exceeding the Means for Response Time and Error of the Experiment as a whole

Frequency (c.p.s.)	Sound level (db)	Average Response Time	Confidence interval $(P=0{\cdot}05, t=2{\cdot}01)$	Average total errors	Confidence interval $(P=0{\cdot}05, t=2{\cdot}01)$
4800–9600	100	0·0980	0·00712	9·00	1·743
2400–4800	100	0·1027	0·00756	9·17	1·772
600–1200	100	0·0915	0·00710	8·13	1·585
150–300	100	0·0942	0·00736	8·25	1·637
75–150	100	0·0951	0·00742		
4800–9600	90	0·0954	0·00721	8·61	1·698
2400–4800	90	0·1005	0·00747	8·83	1·648
1200–2400	90			8·13	1·623
75–150	90	0·0932	0·00742		
4800–9600	80			8·06	1·700
2400–4800	80	0·0938	0·00776		
1200–2400	80	0·0941	0·00743	8·13	1·640
4800–9600	70	0·0935	0·00763	8·08	1·669
2400–4800	70	0·0929	0·00743		
600–1200	70	0·0926	0·00736		
300–600	70	0·0914	0·00657		

The data indicate that the response times tended to be slower and the number of errors greater when the noise levels and frequencies were highest ; the response time and error averages tended to be largest for noises having sound pressure levels at 90 and 100 db ; the frequency range of 2400–4800 cycles per second was associated with the slowest response time and largest number of errors at both the 100 and 90 db levels.

§ 3. DISCUSSION AND CONCLUSIONS

Certain of the present results compare with the findings of previous investigators. Cassel and Dallenbach (1918) found that intermittent sounds are distracting and slow up reaction time. Miles (1953) observed that time scores for ' visual reaction time ' were about 5 per cent longer in the presence of noise in a series of trials which ordinarily might have been expected to result in reduced scores due to additional practice. In a subsequent test, however, Miles noted an inconclusiveness in his results and states, " . . . the results for the effect of intense noise on such simple behaviour as reaction time will vary widely according to individual differences " (p. 90). The tantalizing elusiveness of a concrete determination which will significantly express the presence or absence of a relationship between noise and reaction time is further indicated in the work of Stevens and his associates (Stevens 1941, Stevens *et al.* 1941) who found that in one instance reactions were slower in the presence of noise. However, a critical evaluation (Waring 1946), of the results of that study concluded that the noise under investigation (airplane noise) had no, or at worst a slight, detrimental effect upon motor coordination and reaction time. From the evidence submitted by the present study and others, it may be postulated that noise may lengthen reaction time, but its effect is uncertain.

The tendency indicated by the present study for lower error scores to occur during the quiet spell, may be discerned also in the results of other studies (Laird 1933, Miles 1953, pp. 87, 91).

A number of inferences concerning safety may be found in these results and in those of related studies some of whose conclusions seem to be substantiated by this investigation. For example, statistically it was clear that in the presence of the noises sampled, there was a significant increase in the average response time, number of errors committed and number of errors per unit of production. Thus, it appears that intermittent noise may be considered to have a reducing effect on the individual's capacity for quick and precise execution of coordinated movements. The implications for safety seem obvious.

The tendency for response times to be slower and the number of errors to be greater when the noise levels and frequencies were the highest is noteworthy, particularly since this is an extension of an earlier report (Broadbent 1957). It appears that 90 db, especially for the higher frequencies, is a limit beyond which noise is likely to impair performance. It is curious that this approximates also the limiting noise levels for controlling interference with speech and risk of damage to hearing.

Acknowledgment

This study was made possible by the American Museum of Safety, through its Arthur Williams Memorial Research Fund which has participated frequently in the development of basic safety information.

Appendix

In Tables 3, 4 and 5 the results of the individual subjects are given in rank orders of score. The headings ' 1st half ' and ' 2nd half ' refer to the part of the experiment in which the conditions concerned were experienced, i.e. the scores of one group of subjects are shown in the two outer columns and of the other in the two middle columns.

Men subjects are marked *. Subjects experienced in operating a compound slide rest as a production tool are marked †.

Table 3

Total Errors

Quiet				Noise			
1st half		2nd half		1st half		2nd half	
Subject	Score	Subject	Score	Subject	Score	Subject	Score
29	40	22*	9	18†	20	29	27
45*†	58	18†	11	27	21	33	48
43*	92	27	18	10*†	33	45*†	76
5	94	10*†	20	22*	34	5	90
17*†	94	14*	39	14*	38	30	102
33	98	36	57	36	50	38	109
34*	104	41*†	72	23	64	43*	114
30	107	23	74	37	95	34*	117
38	120	37	91	19*†	125	47	118
47	124	3	120	1	140	17*†	141
46	165	42	124	41*†	146	46	165
32	191	19*†	135	3	170	15	225
35	206	28	143	28	178	32	237
40	229	1	149	9	204	40	250
15	249	52	153	24	213	51	297
51	254	24	181	42	213	35	300
49	262	50	190	52	219	49	302
25*†	273	9	197	44	220	39	354
39	319	7	205	50	236	25*†	363
2*†	343	16	241	16	265	2*†	408
8*	483	44	264	7	274	8*	506
21	793	6	273	11*	286	21	741
		11*	287	6	361		
		12	320	12	371		
		20	381	4	386		
		4	392	13	443		
		31	408	26	461		
		13	422	20	478		
		26	497	48*	492		
		48*	598	31	504		

Table 4

Total Response Times (Minutes)

Quiet				Noise			
1st half		2nd half		1st half		2nd half	
Subject	Score	Subject	Score	Subject	Score	Subject	Score
17*†	0·40	22*	0·03	18†	0·089	33	0·31
33	0·52	18†	0·04	27	0·29	38	0·57
38	0·63	27	0·09	10*†	0·35	43*	0·64
5	0·67	10*†	0·12	14*	0·38	30	0·65
43*	0·69	14*	0·38	19*†	0·79	17*†	0·68
30	0·75	41*†	0·38	1	0·86	5	0·75
34*	0·90	42	0·44	22*	0·87	51	1·00
47	0·95	23	0·46	37	0·91	46	1·22
35	1·12	37	0·69	23	1·13	47	1·32
46	1·15	19*†	0·81	41*†	1·13	32	1·51
32	1·16	1	0·89	28	1·51	15	1·74
51	1·22	3	0·95	52	1·53	34*	1·88
29	1·88	52	1·02	9	1·78	35	2·20
15	1·99	28	1·04	3	1·85	40	2·34
		24	1·32				
25*†	2·13	9	1·56	44	1·86	49	2·45
40	2·18	50	1·84	7	1·89	2*†	2·85
2*†	2·26	44	1·94	24	1·99	39	3·89
39	2·40	7	1·944	16	2·43	25*†	3·93
49	2·43	6	2·15	42	2·47	45*†	4·59
45*†	3·87	16	2·20	50	2·72	29	6·34

Table 4 (*cont.*).—Total Response Times (Minutes)

Quiet				Noise			
1st half		2nd half		1st half		2nd half	
Subject	Score	Subject	Score	Subject	Score	Subject	Score
8*	8·02	11*	2·58	11*	3·24	21	8·76
21	8·86	20	2·98	6	3·61	8*	10·09
		36	3·09	36	3·70		
		4	3·34	4	3·96		
		12	3·37	26	4·62		
		31	4·10	12	4·95		
		26	4·60	20	4·98		
		13	4·79	31	6·19		
		48*	6·14	48*	6·20		
				13	7·18		

Table 5

Productivity Scores

Quiet				Noise			
1st half		2nd half		1st half		2nd half	
Subject	Score	Subject	Score	Subject	Score	Subject	Score
2*†	43·59	48*	35·62	20	34·71	2*†	51·77
21	42·61	20	35·00	4	29·21	17*†	43·17
35	36·21	26	34·98	31	28·83	21	38·78
17*†	35·02	31	33·75	52	28·11	51	32·00
15	33·53	4	31·40	6	27·39	32	31·78
51	29·21	52	31·03	41*†	27·18	15	31·25
49	25·87	1	28·45	26	26·52	35	30·44
8*	24·97	6	28·12	11*	25·27	49	26·31
45*†	24·35	19*†	27·30	42	25·18	45*†	25·70
32	23·09	44	26·76	28	25·17	25*†	25·00
38	22·17	41*†	26·40	13	24·35	8*	23·30
33	22·15	24	25·66	48*	24·06	33	22·96
25*†	20·14	13	25·40	7	23·03	38	22·05
46	18·28	10*†	24·20	1	20·35	43*	22·00
40	16·80	37	24·04	19*†	19·97	40	19·65
34*	16·28	7	23·14	24	19·92	46	18·62
43*	15·78	42	23·08	50	19·73	47	16·18
47	14·54	11*	22·74	37	18·81	39	15·72
39	14·52	12	20·64	10*†	18·68	34*	15·67
30	12·52	28	20·64	12	17·72	5	10·87
5	10·77	50	20·61	44	17·52	30	10·20
29	5·80	23	16·27	18†	17·02	29	2·75
		18†	15·94	3	12·67		
		9	15·45	23	12·08		
		27	13·80	22*	10·76		
		3	13·01	14*	10·02		
		36	11·32	9	9·54		
		14*	9·98	16	9·21		
		16	9·08	36	8·76		
		22*	8·20	27	8·46		

Un groupe des sujets ont exécuté une tâche dans les environs du repos et du bruit. Le bruit a été intermittent, dedans le rang en fréquence de 75 à 9600 cycles, et en les niveaux du son de 70,80,90, et 100 db. L'étude a été expérimentale, mais elle a simulé une situation occupationale.

Il y avait une disposition pour plus des erreurs et moins de précision quand ils travaillaient dans l'environs du bruit. Les temps de la réponse ont été plus lent et le nombre des erreurs plus grand quand les niveaux et les fréquences du bruit ont été le plus haute. Le rang en fréquence de 2400–4800 cycles a été associé avec les temps de la réponse le plus lent et avec le nombre des erreurs le plus grand, par 90 et par 100 db.

Il se montre que le bruit intermittent peut réduire la capacité du individu pour l'accomplissement viv et précis des mouvements mis au même rang. Les implications pour la sûreté et pour des tâches de production semblent évidentes.

Eine Gruppe von Untertanen hat eine Aufgabe in ruhige und in geräuschvolle Umgebungen verrichteten. Der Lärm war aussetzend, in der Reihe des Häufigkeits von 75 bis 9600 Zyklusen, und mit Geräuschrichtlinien von 70, 80, 90, und 100 db. Die Untersuchung war erfahrungsmässig, sondern hat sie eine berufsmässige Lage nachgemacht.

Es hat eine Tendenz für mehre Fehler und weniger Genauigkeit gegeben, als die Arbeit sich n der Geräuschvolle Umgebung ereigneten hat. Die Zeite der Erwiderung waren langsamer und die Anzahl des Fehlers war grosser als die Geräuschrichtlinien und Häufigkeite am höchsten waren. Die Reihe des Häufigkeits von 2400–4800 Zyklusen hat sich mit der am langsamsten Zeite der Erwiderung und der am grossten Anzahl des Fehlers zu beide 90 und 100 db. zugestellt.

Es scheint dass ausgesetzendes Geräusch eine zurückfuhrende Wirkung and der Fahigkeit des Individuum für die lebendige und genaue Ausführung von beigeordnete Bewegungen haben mag. Die Verwicklungen für Sicherheit und für bestimmte Aufgaben der Produktion scheinen augenfällig zu sein.

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THE EFFECTS OF 'MACHINE' LAG ON A SERIAL CHOICE TASK WITH BALANCED AND BIASED INPUT FREQUENCIES

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An experiment is described which was designed to study the effects on rate or responding of (*a*) the frequencies of the various signals to which responses had to be made, and (*b*) the introduction of enforced delays between the appearance of a signal and the making of a response to it. Time taken to respond was found to be significantly lower when one of five alternative signals occurred much more frequently than others, than when the frequencies of all five signals were the same. Enforced delays in responding clearly shifted the modal response time when the input frequencies were biased.

The experiment has affinities to a number of practical tasks and was suggested by a problem arising in the sorting of letters by machine. Certain theoretical implications are also discussed regarding maximum possible rates of responding and the relation of response time to 'information'.

§ 1. Introduction

This study was prompted by a problem encountered by Conrad (1956) in relation to a Post Office automatic letter sorting machine. In this machine the operator is required to press keys according to a code in response to the addresses shown on envelopes which pass in front of him. The rate at which the envelopes appear is determined by the rate at which he makes his responses, each response bringing on the next envelope. The construction of the machine is such that there is a short period after each code is pressed before a second response can become effective and the question arises of whether this delay is likely significantly to slow down the operation of the machine.

In trying to answer this question one has recourse to two areas of research. The first is that which deals with fast serial responding in general, and with self-paced performance in particular. Here it was held for some time (see Hick and Bates 1950) that there was an upper limit of about two responses per second in situations which might be considered analogous in some respects to those encountered in the machine described above. From this point of view one had reason to assume that a delay imposed by the machine on the operator's ability to respond would not slow down performance appreciably, so long as it was substantially less than 0·5 sec. The second area of research concerns that in which information theory has been applied to a number of choice reaction and sorting tasks. These studies have revealed that the time taken per response is, on average, a linear function of the amount of 'information', in the information theory sense of the term, which is transferred from 'input' to 'output' (in the above case from address to keys) in making a response. Evidence and an admirable exposition of the theoretical case has been given by Crossman (1953). The time taken to make individual responses will vary. Some will be substantially slower than average, some appreciably faster. This is particularly the case where the frequencies of different signals are very different or, in the case of the letter-sorting machine, where some addresses are much commoner than others. Introducing differences in the frequencies reduces the information per stimulus as compared with cases in which frequencies are balanced, and the shortening of the *average* time per response resulting from this has been shown by Crossman (1953) and Hyman (1953) to be approximately proportional to the reduction of nformation. But in the first of these experiments the movement time itself was about 0·5 sec and in the other stimuli were given with relatively long ntervals in between. Thus neither experiment showed whether, if the nformation per stimulus was reduced sufficiently by the unbalance in the frequencies of the different stimuli, the rate of two responses per second could be exceeded.

The present experiment was therefore undertaken with two questions in mind. Firstly, can responses be made at a rate appreciably above two per second, especially if the frequencies of different signals are very unequal ; and secondly does a minimum delay between responses slow down overall performance even though the delay is substantially shorter than 0·5 sec ?

§ 2. Method

Apparatus : The display consisted of a row of five small neon bulbs facing the subject with their long axes approximately at eye level about two feet from the subject's eyes. The spacing between centres of bulbs was 1·5 in. The control consisted of five conveniently spaced morse keys placed on a table in front of the subject. The control–display relationships were such that to achieve a correct response the subject had to press the key spatially corresponding to the bulb which was lit. Each pressing of a key, whether correct or wrong, brought on the next light in the series, so that the task was self-paced.

Stimulus sequences : Two series of stimuli were used, each series containing 50 stimuli. The *balanced* series was made up from a table of random numbers with the constraint that no runs of more than two were permitted, and with frequencies and digram structure balanced as closely as possible, i.e. ten stimuli for each of the five sources (2·3 bits per stimulus). The unbalanced or *biased* series was so constructed that one source occurred 34 times, and the other four sources four times each (1·5 bits per stimulus). The connections between the machine generating the series and the five signal lights could be permuted and different permutations were used for each trial.

Enforced delays in responding : The apparatus could be arranged either with or without a constraint upon the timing of responses. The constraint was obtained by disconnecting the response keys from the main part of the apparatus for about 0·35 sec after the beginning of each response. This meant that if the subject pressed a key within about 0·35 sec of a previous response, he display would not change. If the subject kept his finger on the key until he end of the ‘ dead time ’ he could hear the apparatus click and the display would change. He would then have to release the key before being able to make the next response. Observation suggested that in fact waiting on the dead ’ key did not happen very frequently.

Procedure : Two groups, each of six subjects, were used and they had omewhat different training procedures. In the first group, operating throughout without the enforced delay, three subjects were trained on balanced, and hree on biased series, and during this time the balanced sequence did not have the same signal following itself without another in between. This training was followed by one session in which all subjects were given both types of series, half starting with balanced and half with biased. The next session, identical to that just described, was the test session. The second group operated with the enforced delay throughout, and was given both balanced and biased sequences throughout, three subjects starting with balanced, and three with biased on each session. The procedure on the test day was the same as for the first group. The pre-test experience of subjects in the first group was 1650 responses in five days, that for the second group was 1800 responses in three days. It is not thought that these differences in procedure are likely to have had any important effect on the results.

On the test day subjects were given two blocks of six trials each containing 50 stimuli : the first trial in each block was considered a warm-up trial and the results of the five remaining trials were used. Permutations of the biased sequence were chosen in such a way that each of the five signal lamps was lit with greater frequency than the others on one trial during the test. Subjects were told in advance of each trial which this lamp would be. They were instructed to operate as fast and as accurately as they could and were told their time and their error score after each trial.

Scoring : Total times per trial were obtained from a decatron timer to the nearest 0·1 sec. Errors were obtained from an electromagnetic counter. Distributions of individual response times were obtained from a distribution meter on loan from the G.P.O. who also made this piece of equipment. The distribution meter is designed to sort each interval between successive responses into one of eleven categories. The size of categories used was :

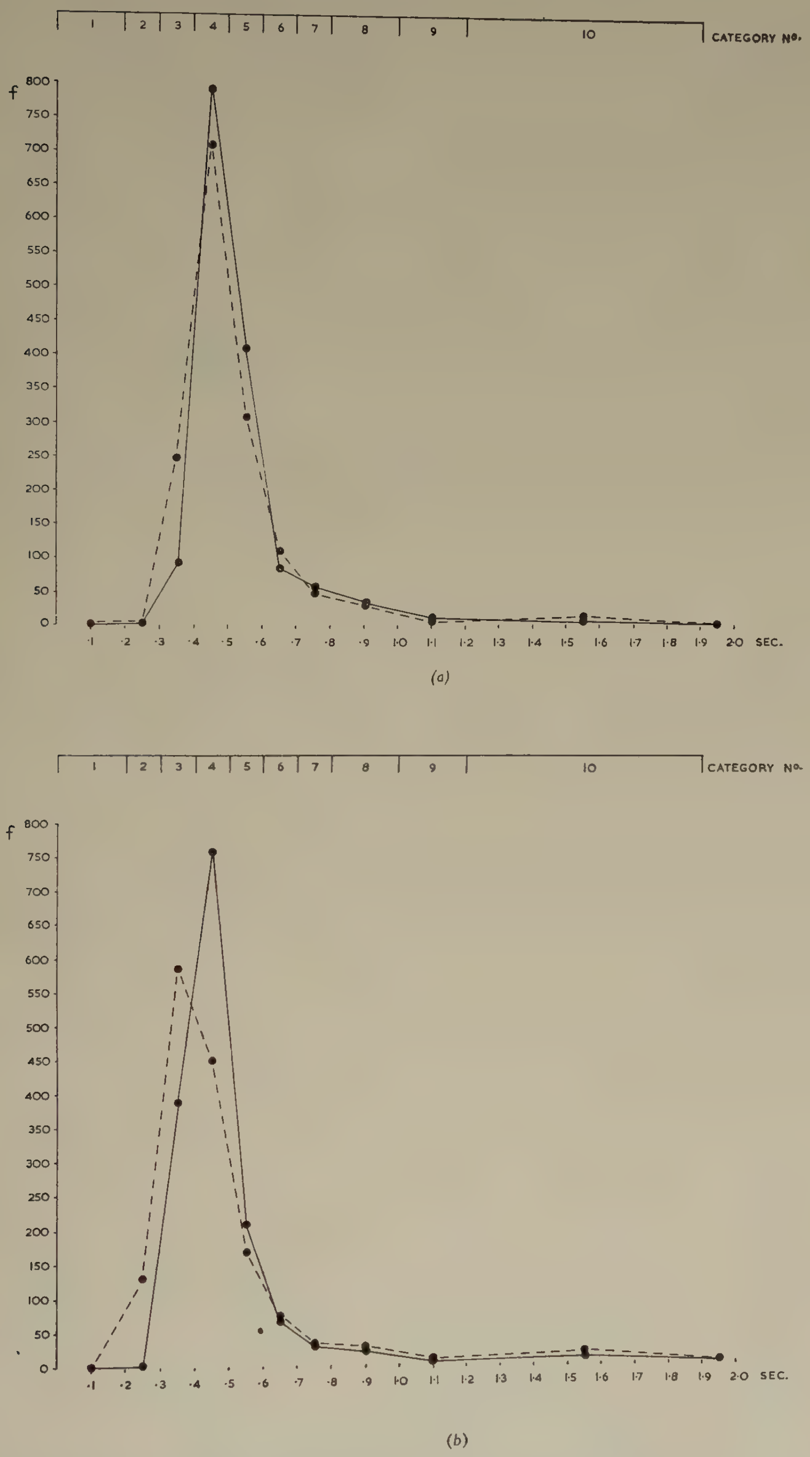
Category	1	2	3	4	5	6	7	8	9	10	11
Duration in sec:	<0·2	<0·3	<0·4	<0·5	<0·6	<0·7	<0·8	<1·0	<1·2	<1·9	1·9 and longer

For the purpose of presenting results the readings contained in the largest category were not included. In the great majority of cases this category contained only the reading obtained for the first response of each trial, which was large because circuits were not arranged to cancel the device when starting the series.

§ 3. RESULTS

Mean values of response times and error percentages are presented in Table 1. It can be seen that both groups took less time with biased than with balanced series. All members of the group working without enforced delays and four out of the six working with enforced delays showed this effect. The rates of responding rose appreciably above two per second, especially among the first group of subjects.

The distributions of response times are graphed in the figure and confirm the indications of Table 1 regarding the effects of enforced delays. For the balanced series the distributions with and without delay are closely similar, although the latter is shifted slightly to the left. For the biased series the distribution with delay is shifted very clearly to the left so that the mode falls in category 3 instead of category 4. The delay thus seems appreciably to have affected the speed of response with the biased series, but not with the balanced.



Frequencies of responses (*f*) in different time-categories.
(a) Balanced series. (b) Biased series. Dotted lines: without enforced delays in responding. Solid lines: with enforced delays. The frequencies for individual subjects are given in Appendix, Table 3.

Table 1. Mean Times, Rates of Responding and Error Percentages

Series	Measure	Group working without enforced delay	Group working with enforced delay
Balanced	Secs per response	0·485	0·498
	Responses per sec	2·06	2·01
	Percent errors	4·1	3·5
Biases	Secs per response	0·419	0·453
	Responses per sec	2·39	2·21
	Percent errors	3·2	2·9

The mean times were calculated from the times per trial. It should be noted that these mean times per response include the duration of the enforced delay response. The rates of responding are the reciprocals of the mean times ; the errors are expressed as percentages of the total number of responses in each condition, i.e. 1500. Data for individual subjects are given in the Appendix, Table 2.

An analysis of variance carried out on subjects' mean times per response showed a highly significant effect between balanced and biased series. The effects due to the use of the enforced delay, although appreciable, especially with the biased series were not significant, nor was the interaction between delay and type of series. The effect of order of presentation was not significant but the interaction between this effect and that due to the use of balanced or biased series was significant.

§ 4. Discussion

From a practical point of view the results obtained in the present experiment throw some light on the possibility of detrimental effects of machine lags in those cases in which the operator can see the next signal to be dealt with without being able to respond as soon as he is ready to do so. One can think of a number of situations in which this might apply, i.e. where there is a measure of independence between the rate at which signals arrive and the rate at which operators can follow, the limiting factor being lags in the control system such as times required for the system to be cleared. It is evident from the distributions of response times that since operators are in fact able to deal more rapidly with a biased input such delays may be more detrimental in such cases.

Having said this much it is necessary to make certain qualifications. The two most important are that in the present experiment only one duration of delay was used, as well as only one amount of bias. Concerning the latter point it may be doubted whether there are many instances in which the bias used here is exceeded in real life situations, except perhaps in some inspection tasks. On the other hand the duration of the delay was chosen somewhat arbitrarily to be below the mean response rates. While it seems reasonable to assume that duration of delay as a function of mean response rate will have effects of varying magnitude, inspection of the distributions makes it clear that it is not at present possible to predict the size of the effects. The use of the delay did not seem to produce a simple shift, but was apparently compensated for to some extent, so that in the case of the balanced input frequencies the difference of mean response times was relatively small. This leads to a further qualification. The subjects in the present experiment were operating at or near the limit of their performance over very short periods of time. The largest difference in mean response times found was 0·066 sec, and the effect due to the delay with the biased series was only 0·034 sec on the average. No evidence is available to help one to say what effects would be when performance had to be continued for longer periods, say 45 minutes or so at a time for several weeks on end.

The main point of interest from the theoretical point of view is concerned with the performance of subjects in the group working without enforced delays. When operating with the balanced input they were performing at an average rate of about two responses per second and were able to improve on that rate when operating with the biased input. In other words, they were able to take advantage of the reduced information content. Now, while on the one hand there is reason to believe that the ' limit ' of two responses per second for manual responding (Hick and Bates 1950) can be exceeded under certain conditions, variation in information content achieved by varying the number of *equiprobable* alternatives does not appear to be one of these conditions (Alluisi, Muller and Fitts 1957). In the case of the experiment just presented reducing the information content by varying the *bias* did however have a significant effect on performance. Thus a simple experiment is suggested to test the hypothesis that one of the pre-conditions for obtaining a two-responses per second limit is equiprobability rather than information content of alternative stimuli : one would have to compare self-paced performance under at least three conditions, e.g. 5-choice equiprobable, 3-choice equiprobable, and 5-choice with 68 per cent bias (in the last two of these conditions the average information per stimulus is about the same). On the above argument one would expect there to be no difference in mean times to respond between the first two conditions, but a significant difference between these two and the third condition. It is hoped to carry out such an experiment in the future.

APPENDIX

Table 2 shows the mean times (total times per trial summed for five trials and divided by 250) for each of the twelve subjects, and their error percentages (errors summed for five trials and expressed as a percentage of 250).

Table 2. Individual Subjects' Mean Times per Response and Error-Percentages

	Balanced series		Biased series	
	Time per Response	Errors	Time per Response	Errors
Without enforced delay	Seconds	per cent	Seconds	per cent
A	0·496	3·2	0·420	3·2
B	0·447	2·8	0·397	2·4
C	0·512	5·6	0·428	2·4
D	0·437	4·0	0·396	2·4
E	0·574	4·0	0·461	4·0
F	0·444	4·8	0·410	4·8
With enforced delay				
G	0·459	5·2	0·437	3·2
H	0·466	5·2	0·488	1·2
I	0·561	2·8	0·426	3·6
J	0·510	3·2	0·508	4·4
K	0·509	2·8	0·439	2·4
L	0·484	2·0	0·417	2·8

Table 3. Individual Subjects' Response Distributions. x=balanced, y=biased. The letter indicating the series given first is in italics

Category		<0·2	<0·3	<0·4	<0·5	<0·6	<0·7	<0·8	<1·0	≤1·2	<1·9	Sec
Subject Without enforced delay												
A	x	—	—	8	133	84	9	6	3	1	1	245
	y	—	19	102	79	23	9	5	7	1	—	245
B	x	—	1	51	144	29	13	4	1	—	1	244
	y	—	34	86	78	31	6	4	1	—	3	243
C	*x*	—	—	44	97	49	28	12	10	2	3	245
	y	—	12	102	79	24	11	8	4	2	3	245
D	x	—	1	60	137	44	3	1	—	—	—	246
	y	—	49	80	70	31	14	1	1	—	—	246
E	*x*	—	—	10	80	64	48	21	14	2	5	244
	y	—	9	88	70	37	20	6	10	1	4	245
F	*x*	—	—	72	118	36	7	5	3	—	3	244
	y	—	4	128	71	19	12	6	1	—	4	245
Total	x	0	2	245	709	306	108	49	31	5	13	1468
	y	0	127	586	447	165	72	30	24	4	14	1469
With enforced delay												
G	x	—	—	16	178	40	5	3	1	1	1	245
	y	—	—	73	129	30	8	3	2	—	2	247
H	x	—	—	39	137	44	13	8	2	—	2	245
	y	—	—	44	126	39	14	13	9	—	—	245
I	*x*	—	—	1	86	98	22	21	12	1	5	246
	y	—	—	66	150	17	9	—	2	—	—	244
J	x	—	—	—	110	117	11	3	2	2	1	246
	y	—	—	2	138	74	19	7	2	—	5	247
K	*x*	—	—	8	136	59	22	7	7	3	1	243
	y	—	—	72	132	25	8	3	4	—	1	245
L	*x*	—	—	26	142	51	10	12	2	2	—	245
	y	—	—	130	82	22	8	2	—	1	—	245
Total	x	0	0	90	789	409	83	54	26	9	10	1470
	y	0	0	387	757	207	66	28	19	1	8	1473

Table 3 shows the distributions of times for individual subjects. These distributions were obtained by summing for each subject the separate distributions for five trials. They do not include the readings in the category above 2 seconds, so that there should be 245 readings for each subject. In actual fact there was a range of 243–247 which is thought to be attributable to mechanical counter faults. It is worth noting that means calculated from these distributions were all slightly larger than those shown in Table 1, on the average about 0·02 sec. Since these means were calculated with certain assumptions about distributions within categories the reliability of the data is thought to be satisfactory. It will be noticed that for the balanced series all the modes of the group working without enforced delays were in the interval labelled 0·5 sec, and four of the six modes in the group working with delays were similarly placed, the other two subjects having incidences of responses in that category only very little smaller than that of their modes in the next category. With the biased series all six subjects in the former group have modes in the category labelled 0·4 sec, but only one of the six subjects in the latter group achieved a mode in that category, the other five have their modes in the next category, i.e. in the same place as for the majority with the balanced series.

Description d'une expérience destinée à faire connaître l'action sur la vitesse de travail et sur la réponse produite par (*a*) les fréquence des signaux divers auxquel on devait répondre et (*b*) des retards forcés qu'on introduirait entre le signal et la réponse qu'il devait susciter. Le temps qui s'écoulait entre le signal et la réponse se trouvait être plus bref d'une espace significative quand un des cinq signaux alternants se produisait beaucoup plus fréquemment que les autres, que quand tous les cinq avaient la meme fréquence. Des retards imposés à la réponse avaient sans aucun doute pour résultat de changer le temps modale de la réponse.

Cette expérience se rapporte a plusieurs tâches pratiques et fut suggérée par un probléme qu'on rencontra en classant des lettres par moyen d'une machine. Il est question aussi d'implications théorétiques relatives aux vitasses maximales de réponse et à la relation du temps de la réponse à ' l'information '.

Es wird ein Experiment beschrieben, mit dem ermittelt werden sollte, wie (*a*) die Geschwindigkeit der Beantwortung verschiedener Signale durch die Frequenz dieser Signale beeinflusst wird und wie sich (*b*) die Einführung zwangsläufiger Pausen zwischen der Beantwortung eines Signals und der Darbietung des nächsten Signals auswirken. Die Zeit für die Beantwortung eines Signals war signifikant kürzer, wenn eines von 5 verschiedenen Signalen viel häufiger erschien als die anderen, als wenn die Frequenzen aller 5 Signale gleich waren. Zwangsläufige Verzögerung der Darbietung der Signale ändert deutlich das zeitliche Verhalten der Beantwortung.

Das Experiment hat Bedeutung für eine Anzahl praktischer Aufgaben und wurde angeregt durch das Problem der Brief-Sortier-Maschine. Es wurde auch in Zusammenhang mit der Frage der maximal-möglichen Reaktionsgeschwindigkeit und der Beziehung zwischen Reaktionsgeschwindigkeit und ' Information ' diskutiert.

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BEHAVIOUR IN CONTROLLING A COMBINATION OF SYSTEMS*

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The state of a manually controlled system or combination of systems depends upon a balance between the skill of the operator and the difficulty of his task. When the difficulty of the task is varied by increasing the number of systems which have to be controlled, some change in the pattern of performance can be expected. It is possible to identify the parameters of performance which can be adjusted to meet the increasing demands of such a situation, and to describe how they are related to each other and to overall performance.

This analysis has been applied to a task in which the pointers of several dials which tend spontaneously to deviate have to be kept as nearly in alignment as possible, and an experiment with this task has shown ways in which subjects adapt to changes in the number of dials (and controls) involved.

§ 1. Introduction

There are a number of situations where one operator has to work on several control systems at the same time. The situation of piloting aircraft is of special interest, but there are many other examples to be found in the field of communications and industry generally. This study refers particularly to the case of continuously variable information being presented to the operator, where he has to operate controls in a certain way in accordance with the displayed information, and where he has to do several such tasks concurrently.

There has been some previous research on related but slightly different tasks. Mackworth and Mackworth (1956) and Conrad (1955, 1956) have studied the effects of variation in the number of channels in which significant signals for action appear. They have been investigating the discontinuous case where one waits for a signal and then does something, as opposed to the continuous case where there is always or nearly always plenty to do and it is just a matter of finding time to do it. Conrad has drawn attention to the importance of the underlying behaviour upon which the overall success of a complex operation depends.

The state of a control system depends upon the balance between the ability of the operator and the difficulty of his task. Where there are multiple control systems in use together, how is this balance achieved ?

Consider, for example, a continuous compensatory tracking task, where the input is fixed and the system is subject to a disturbance of constant velocity and the error signal is displayed to the subject as when baling-out a leaky boat at sea. If this original task is interrupted by the introduction of a second task, such as a leak in another compartment of the boat, or several more tasks of the same kind, the operator will have to skip about from one to another, and it will be some time before he will be able to get back to the original task. Several questions arise, such as, will the situation get out of hand? If not, how does the man adapt himself to the situation?

To answer questions like these it is convenient to analyse the sequence of events into two phases: the interruption phase when a particular channel is left unattended while other things are being done, and the control phase when that channel is being dealt with.

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* This article is based on part of a Ph.D. thesis approved by the University of London.

During the interruption phase the state of affairs in terms of the size of the error signal usually gets worse, and during the control phase it usually gets better. Equilibrium is achieved if the error which mounts up during the interruption phase is on the average cancelled out in the control phase. In many cases one is not content just to maintain some kind of equilibrium, but one also attempts to minimize some overall measure of performance. The measure used in this study is the time integral of the error considered without regard to sign, from which the mean absolute value of the error regardless of sign, usually called the modulus mean error, is readily derived.

During the interruption phase this integral increases by an amount equal to the area under the error-time curve. This curve may take any one of the forms shown in Fig. 1, according to the size and sign of the residual error remaining after the previous corrective movement of the control.

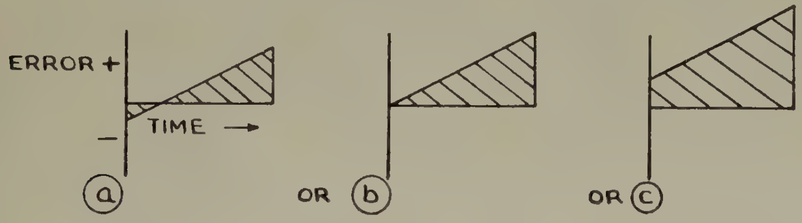

Figure 1. Increase with time of error due to interruption.

The shaded area depends upon the duration of the interruption, the velocity of the disturbance, and the residual error. If we let

e_r = residual error, positive or negative,
v = velocity of disturbance,
t_i = duration of interruption,

then the areas are given by the following expressions:—

$$(a)\quad \frac{vt_i^2}{2}+\frac{e_r^2}{v}+e_rt_i$$

$$(b)\quad \frac{vt_i^2}{2}$$

$$(c)\quad \frac{vt_i^2}{2}+e_rt_i.$$

The duration of the interruption depends in turn upon the number of systems requiring attention, the amount of time spent in controlling each of them, and the amount of time lost in each change-over from one to another.

Let n = number of systems requiring attention,
t_m = average time lost in each change-over,
t_c = average duration of control movements,
t_i = average duration of the interruptions,

then, assuming that each system is dealt with in turn,

$$t_i=nt_m+(n-1)\,t_c.$$

The velocity of the disturbance is usually not under the operator's control. The size and sign of the residual error depend upon the accuracy of the control movement which preceded the interruption and the operator's skill in anticipating the coming disturbance.

During the control phase the error-time integral also increases. Here again there are three possible types as shown in Fig. 2.

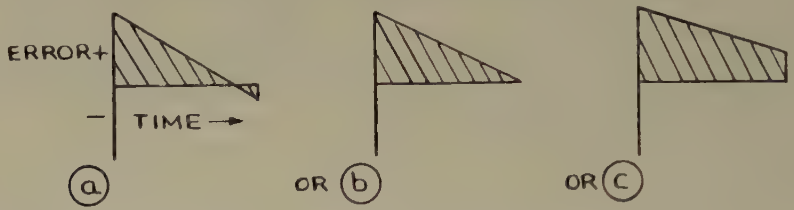

Figure 2. Decrease with time of error according to type of corrective action taken.

The shaded area depends upon the duration of the error, the rate of correction, and whether or not the correction ends up with a residual error of opposite sign to the error in which it began. In the leaky boat example, case (*a*) would be best if only we could have a negative quantity of water aboard !

The important features of the operator's task, therefore, are the velocity of the disturbance and the number of channels or control systems that he has to work on. The important features of the operator's performance are the duration of his movements both in control and in changing over from one control to another, the accuracy of his control movements and his ability to anticipate disturbances.

§ 2. AIM

The experiment to be described below was carried out in order to find how alteration of the characteristics of the task affects the pattern of the operator's performance, and how far and by what means he can overcome increases in the difficulty of the task by adapting himself to the needs of the situation.

§ 3. APPARATUS

A test apparatus was designed to make it possible for a subject to work at one, two, three, four or five tracking tasks at a time. The tasks were as nearly identical as possible and they were effectively independent of each other. The subject sat at a console having five dials and five knobs as shown in Fig. 3. Each knob was a positional control for its corresponding dial. Disturbance signals were provided which produced simple harmonic misalignments of the pointers of one cycle per minute, with maximum amplitude of ± two scale divisions or $\pm 4{\cdot}5^\circ$ of angular movement. These pointers had to be corrected to their centre zeros by the subject. The disturbances were arranged to be out of phase with each other, so that the pointers were all behaving differently at a given moment.

The theoretical analysis given above dealt with the simple case of a steady uni-directional disturbance, and it requires to be extended to deal with an oscillating disturbance. From the experimental point of view an oscillating signal is more convenient and there need be no difficulty in its mathematical treatment.

Twenty subjects were tested. They were set to work to control one, two, three, four or five pointers at a time, using one hand only, and instructed to work systematically round the set of controls and dials in use, giving them equal attention, and to try to keep the pointers as near as possible to zero all the time. Each subject, after practice, worked at each number of dials for five minutes. The conditions were presented in different orders to different subjects so as to minimize learning effects. Measurements were made of the integrated modulus error for both the corrective movements and the interruption periods for each separate control system, the durations of these phases were measured, and the number of corrective movements made during the session was counted. From these measurements several significant parameters were derived.

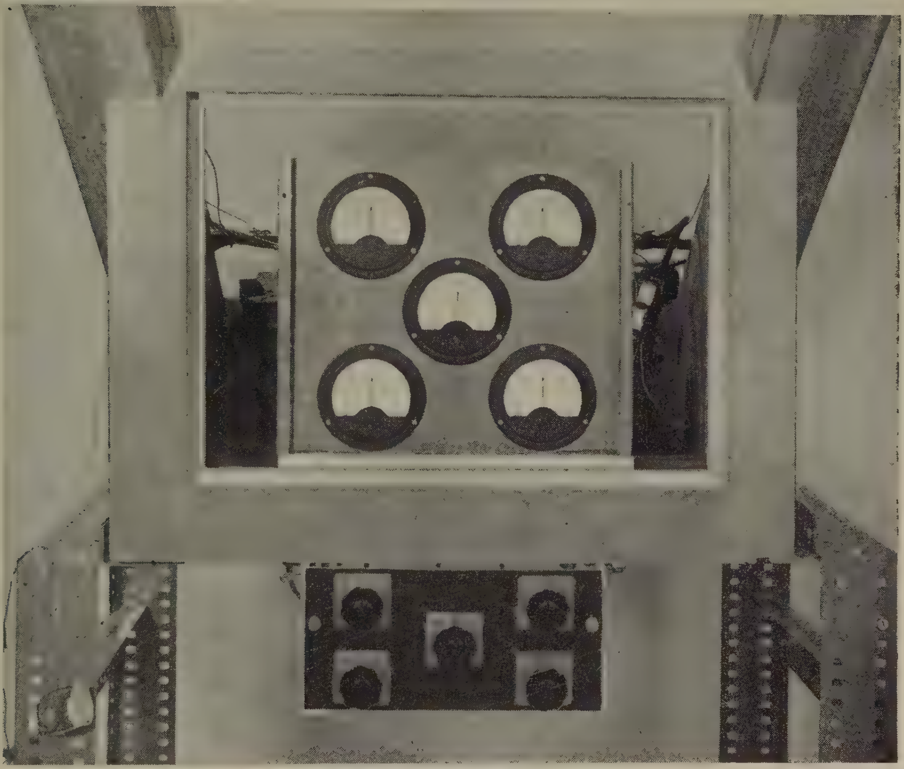

Figure 3. The test apparatus.

§ 4. RESULTS

The results were computed from both individual and group data. Analysis of variance was carried out on the individual results of the five main measures: the modulus mean error for interruption and for control movements, the average duration of interruptions and control movements, and the number of movements per trial. The means and standard errors are shown in Table 1. All measures were shown to differ significantly between different numbers of dials. With the exception of the modulus mean errors, all derived scores illustrated have been computed from the average values of the five main measures of performance.

Table 1. Means and Standard Errors of the Main Measures

Measure	Number of Dials 2 Mean	S.E.	3 Mean	S.E.	4 Mean	S.E.	5 Mean	S.E.
Duration of control movements (in secs) (t_c)	1·05	0·082	0·92	0·061	0·88	0·064	0·89	0·073
Duration of interruptions (in secs) (t_i)	2·96	0·22	4·14	0·25	5·12	0·29	6·41	0·39
Rate of working (in movements per trial) (m)	165·30	5·74	191·85	12·85	217·95	16·77	225·00	18·23
Modulus mean error (control) (in scale-divisions per dial)	0·10	0·009	0·15	0·010	0·19	0·017	0·24	0·018
Modulus mean error (interruption) (in scale-divisions per dial)	0·11	0·008	0·18	0·012	0·25	0·015	0·33	0·021

The amplitude of control movements required to keep the system in equilibrium increased with the number of dials in use (Fig. 4). The duration of the control movements (t_c) decreased with more dials, flattening off between four and five (Fig. 5). The average speed of control movement increased in direct proportion to the number of dials (Fig. 6), and showed no flattening.

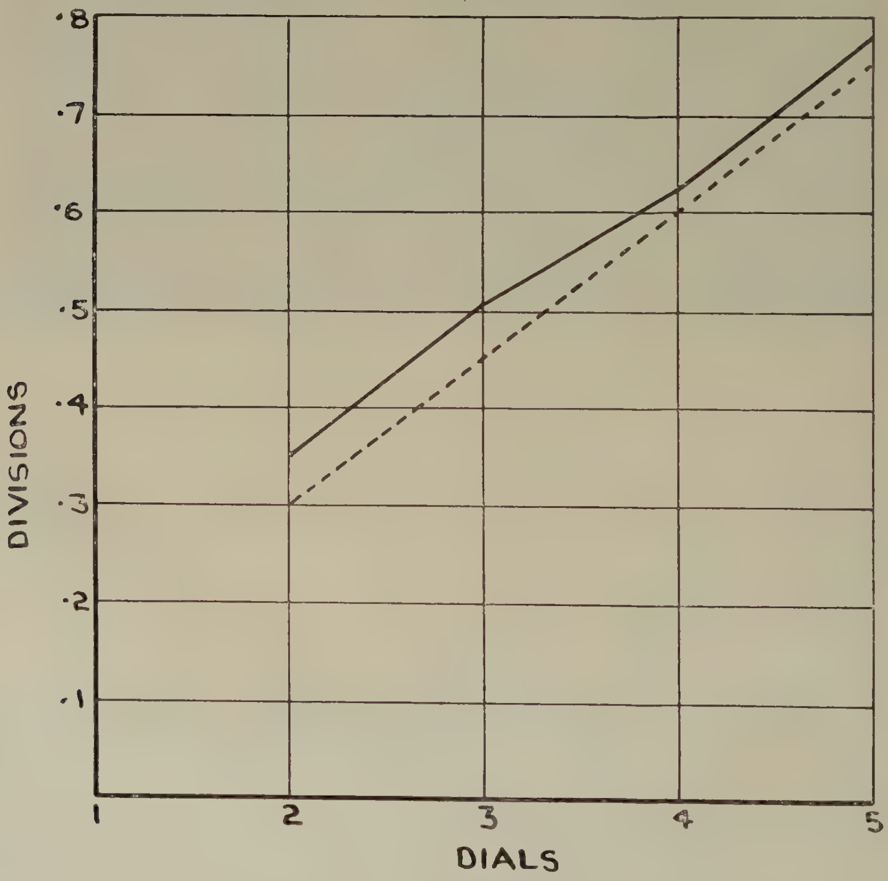

Figure 4. Amplitude of control movements (solid line) and error built up during interruptions (dotted line).

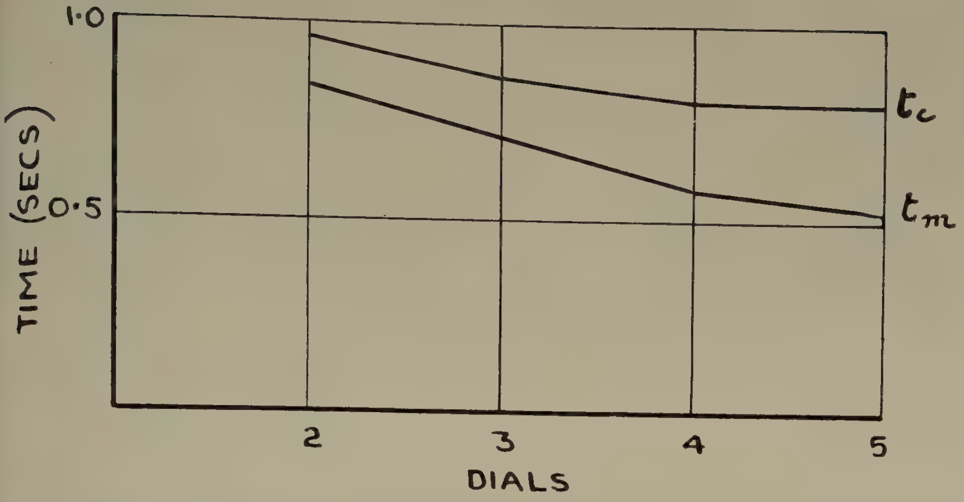

Figure 5. Duration of control movements (t_c) and of changeover movements (t_m).

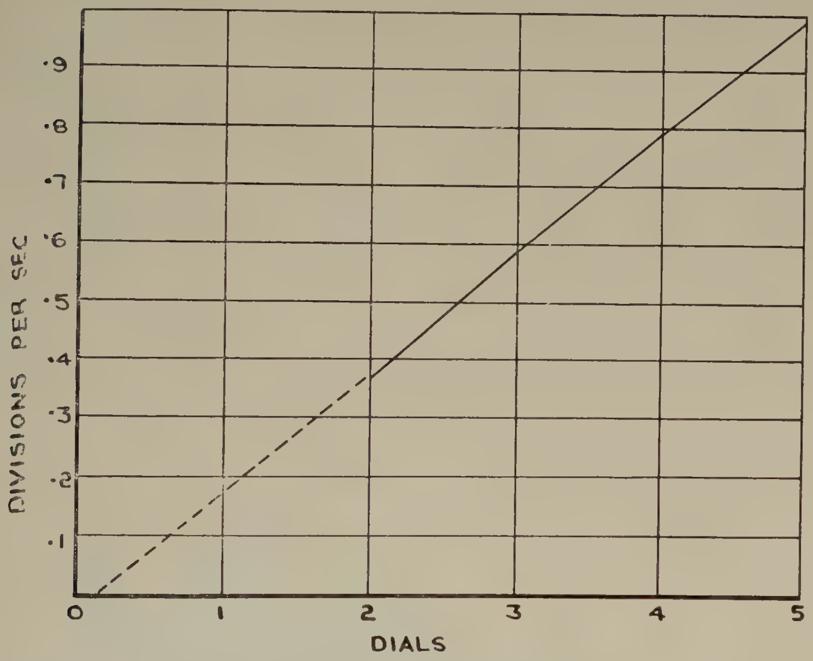

Figure 6. Speed of control movements.

In the arrangement of knobs that was used, the average path of a hand movement was more or less the same regardless of the number of dials. The duration of these movements (t_m) decreased as the number of dials increased (Fig. 5). The frequency with which both control movements and movements from dial to dial were made also increased with the number of dials (Fig. 7).

As has been explained earlier, an increase in the number of tasks would be expected to increase the duration of the interruptions in the continuity of control of any one system. Figure 8 shows the changes found in the experiment, compared with a dotted line indicating how the interruption periods would have increased and allowed large errors to build up if the rate of working had been kept constant.

Owing to over-corrections, the errors which did build up during the interruptions were of slightly less amplitude than the control movements seen in Fig. 4.

Figure 9 shows how subjects operating on two or three dials had a tendency to anticipate the coming disturbance and allow for it in advance thereby reducing the next misalignment that was to be faced. As the number of dials to be controlled increased, and the pace quickened, this forward-looking behaviour became less evident in the results.

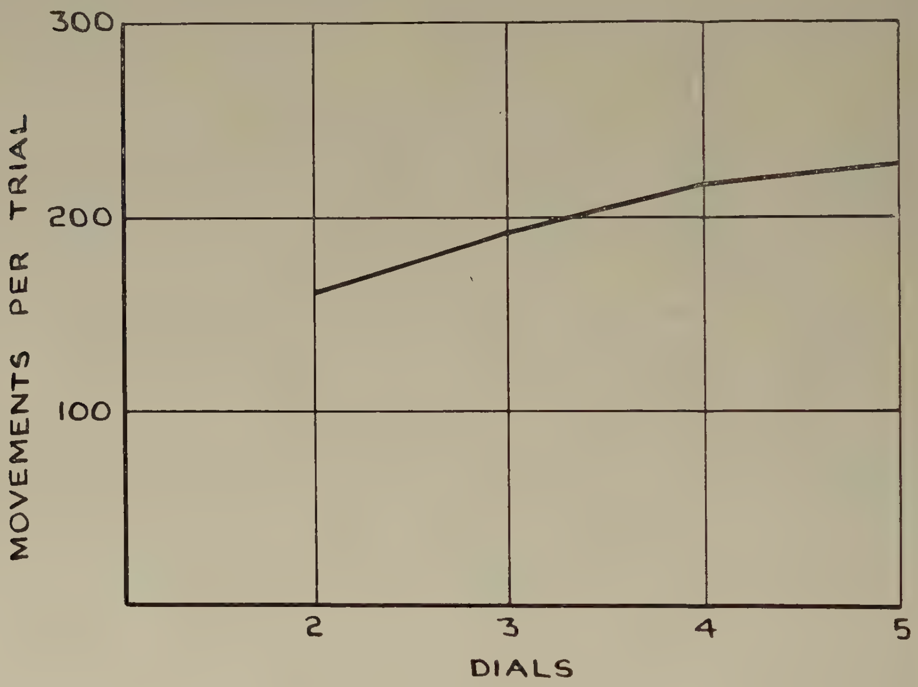

Figure 7. Rate of working (m).

Figure 10 is an idealized combined diagram showing how all these different quantities fit together. The up-slopes represent the movement of a pointer during the interruption phase when subjects were busy attending to the other dials, and the down-slopes represent the path of the pointer during a corrective control movement.

The modulus mean errors are given in Fig. 11 showing the average number of scale divisions by which a dial pointer was away from its centre zero during a five-minute trial. The means are given separately for the control phase and the interruption phase. The results for one dial would have been of interest here but they have not been included because it was found that performance on one dial was too accurate to permit reliable measurement. The curve for the overall performance, taking both phases together, lies between the two lines given in this figure.

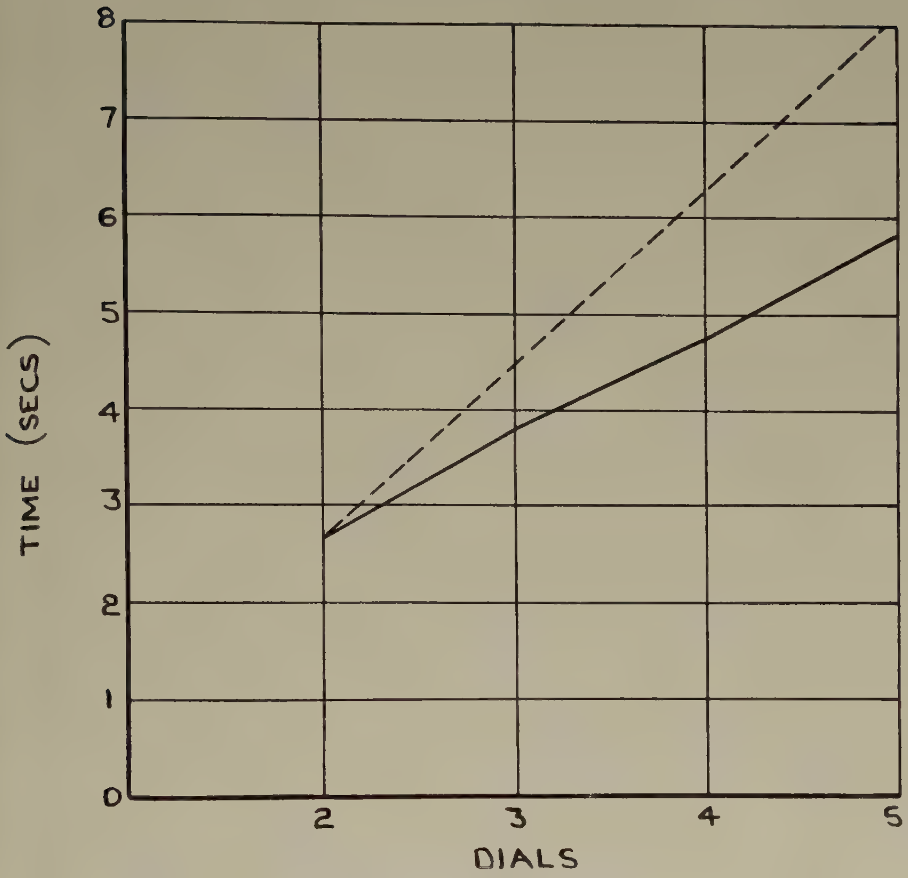

Figure 8. Duration of interruptions (i_i).

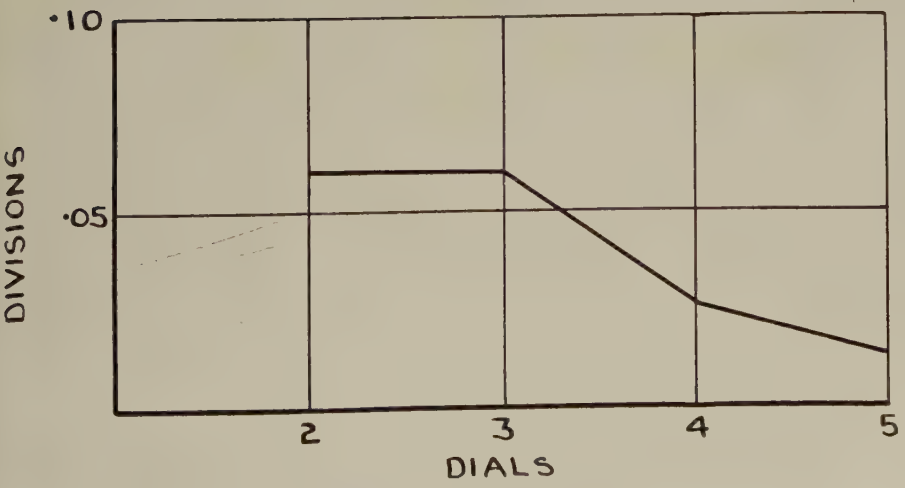

Figure 9. Anticipations.

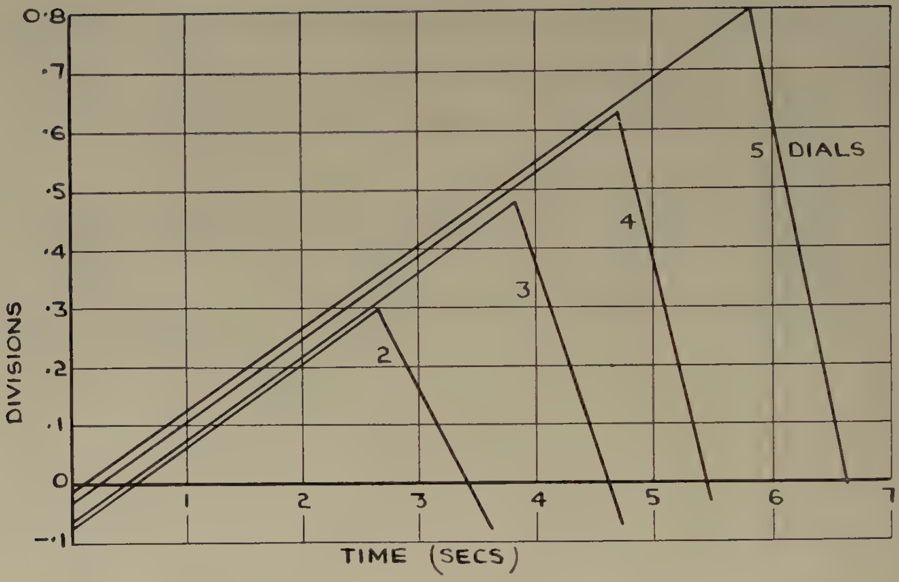

Figure 10. Changes in control equilibrium with increasing numbers of dials.

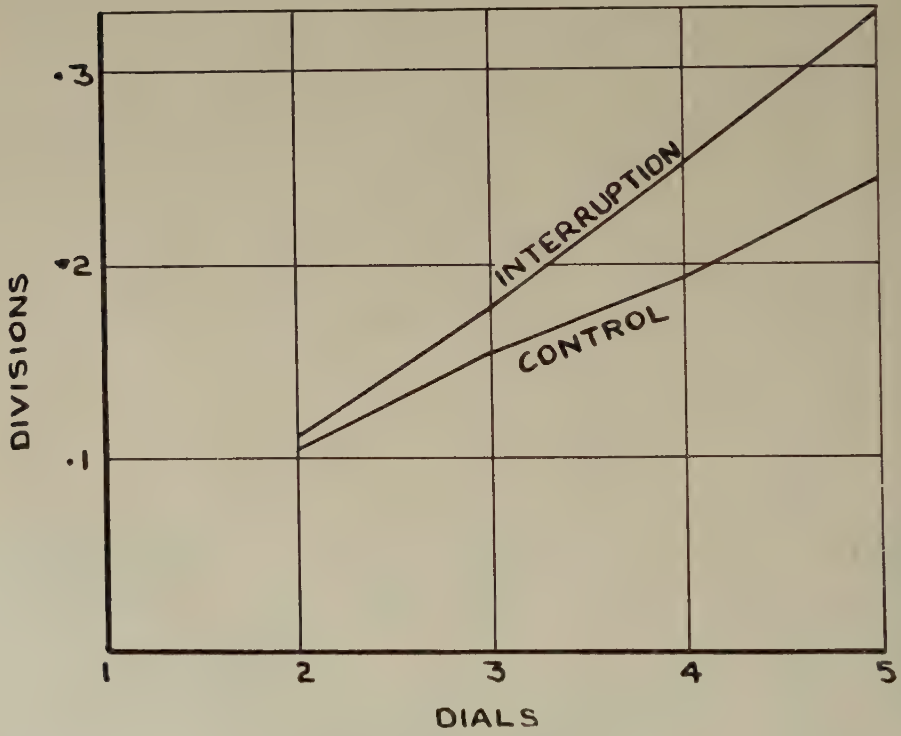

Figure 11. Modulus mean error.

§ 5. Discussion

It has been shown that in terms of the overall measure of performance, namely the modulus mean error, the situation deteriorated considerably as the number of dials increased, but we know from the results of the more elementary measures that the operator did much to prevent the deterioration. He made quicker change-over movements from one control to the next, he made quicker control movements, and he anticipated coming events. Over-all measures of performance conceal the details of behaviour, both those that are adaptive, and those that are not.

It is interesting that increasing the speed of work is a mode of adaptation that was by no means exhausted in this experiment. The speed of control movements, for example, increased in direct proportion to the number of dials and showed no signs of falling off under the greatest number. On the other hand, the ability to make useful anticipatory adjustments of the controls soon faded away. The suggestion has been made to the author that if the relationship found between anticipation and number of signal sources has generality, such that it occurs in all similar situations, then it may help to explain why advance information of coming events, which saves the operator the trouble of anticipating, is particularly useful in situations where the operator is working under conditions where many possible sources of signals have to be watched at the same time.

This increase in the speed of working seems to be a natural response to the change in the number of signal sources, a way of adapting to the demands of the situation which comes quite spontaneously. Most of the subjects were not aware of any relationship between their rate of work and the complexity of the task, and they all said that they had definitely not made a conscious decision that the best strategy would be to work faster with more dials.

Some of the results of this experiment could not have been predicted from any study of performance on a single control system. Two of them are particularly worthy of further attention, both being cases of a parameter increasing in proportion to the number of dials in use. For two to five dials the average speed of turning the control knobs was 0·2 scale divisions per second per dial. The average size of the error built up during the interruption phase was 0·15 divisions per dial. It was as though the operator used as his criterion of performance the error or misalignment, which was after all what he actually saw every time he turned his attention to another dial. He responded to this visual stimulus with a control movement of proportional velocity. He still had freedom to leave the pointer wherever he wished. Then he moved on to the other dials at such a rate that he would find an error proportional to the number of dials waiting for attention on the original dial when he returned to it.

The findings regarding the rate of control movements show a relationship which has been well authenticated (Barnes 1946, Fitts 1954) and particularly accord with those reported by Searle and Taylor (1948) in a closely related study. Their task was in a discontinuous situation where sudden error displacements had to be corrected and the timing of the corrective movement was independent of previous corrections. These authors do not discuss the spontaneity or absence of deliberation in the relationship between amplitude and speed of movement, but they do emphasize the perceptual aspect of the situation and the “ factors of internal set and expectancy ”, which they suppose may vary with the conditions of presentation. They suggest that the subjects attempt to make each correction in a certain length of time, regardless of the required effort, and that their increased speed is necessary to prevent an undue increase in the time of exposure.

It is clear that work on one channel is quite different from work on a number of channels, both in the pattern of activity and in effectiveness. As the load increases, from two continuous channels upwards, the overall standard of work steadily deteriorates, but it does not deteriorate as a simple function of the number of systems. The operator has several ‘ tricks up his sleeve ’ for adapting to the increasing demands of the situation, and he does not bring them all into play at once. This adaptibility is normally concealed in overall measures of performance, and can only be revealed by extracting the details of behaviour and demonstrating how they interact and fit together to make a skilled performance.

L’état d’un système, ou d’une combinaison de systèmes, contrôlés à la main, dépend d’un equilibre entre l’adresse de l’opérateur et la difficulté de sa tâche. Quand la difficulté de la tâche est variée par moyen d’augmenter le nombre de systèmes qui doivent etre contrôlés, on peut s’attendre à un changement quelconque dans le caractère du rendement. Il est possible de distinguer les paramètres de rendement qu’on peut régler selon les exigences croissantes d’une telle situation, et de décrire comment ils se rapportent l’un à l’autre et au rendement hors tout.

Cette analyse a été appliquée à une tâche dans laquelle les aiguilles de plusieurs cadrans qui tendent à dévier d’eux-mêmes ont à être maintenues alignées autant que possible, et une expérience avec cette tâche a démontré chez les sujets des façons différentes de s’accommoder à des changements dans le nombre de cadrans et de contrôles dont il s’agit.

Der Stand eines manuell kontrollierten Systems oder einer Kombination von Systemen hängt von einem Gleichgewicht zwischen der Geschicklichkeit des Arbeiters und der Schwierigkeit der Aufgabe ab. Wenn die Schwierigkeit der Aufgabe dadurch vergrössert wird, dass die Zahl der zu kontrollierenden Systeme vermehrt wird, sind Aenderungen in der Art der Ausführung zu erwarten. Es ist möglich, zahlenmässig zu erfassen, wie die Güte der Ausführung mit zunehmender Schwierigkeit der Ausführung sich verändert.

Diese Analyse wurde bei einer Aufgabe durchgeführt, bei der die Zeiger verschiedener Zifferblätter, die spontan von einer vorgegebenen Stellung abwichen, in dieser festzuhalten sind. Es zeigte sich, wie verschiedene Personen ihre Leistung einer veränderten Zahl von Zifferblättern anpassen.

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WARMTH AND PERFORMANCE: AN INVESTIGATION IN THE TROPICS

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An account is given of an experimental investigation at Singapore into the effect of unusual levels of environmental warmth on the performance of skilled tasks by young European men living in the tropics.

Three experiments on manual tracking, one on prolonged visual watch-keeping and one on high speed decision taking are reported.

Broadly speaking the main findings of previous experiments on artificially heat-acclimatized men were confirmed. Performance first deteriorated somewhere between about 81° and 86°F on the effective temperature scale, although there was some evidence that the critical region was lower for warm humid climates than for warm dry ones. The men at Singapore appeared to be rather more disturbed by unusually cool climates than artificially heat acclimatized men in England.

§ 1. INTRODUCTION

RESEARCH during and immediately after World War II showed that young men living in a temperate climate performed a variety of skilled tasks less effiicently when they worked for one to three hours in unusually warm conditions (Weiner and Hutchinson 1945, Viteles and Smith 1946, Mackworth 1946, 1947, 1950). Decrements in performance occurred even though the men had been accustomed in most instances to working daily in warm humid atmospheres for several weeks immediately before the experiments. There seemed to be a somewhat critical region on the Effective Temperature Scale (Houghton and Yaglou 1923, 1924, Bedford 1946) from about 81° to 86°F (reported in error as 83° to 87·5° by Mackworth (1950)) over which performance first began to deteriorate.

The experiments reported below were conducted in the experimental climatic chambers of the Medical Research Council's Royal Naval Tropical Research Unit at Singapore. The young servicemen who acted as subjects had been living in the tropics for at least six months, and generally for one to two years. It was therefore possible to assess the performances of men accustomed normally to a high level of warmth, when they worked at temperatures similar to those used in the earlier experiments on artificially acclimatized men. In this respect the experiments at Singapore provided an opportunity of validating the main findings of the earlier work on the effect of environmental warmth on performance.

§ 2. SUBJECTS AND GENERAL PROCEDURES

The subjects at Singapore had volunteered to take part in the experiments with the promise of a small increase in pay and some additional leave. They were physically fit, free from skin infections and had been living in the area for at least six months.

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Before and after every period in the climatic chamber all subjects were weighed nude, and their rectal temperatures were measured by mercury in glass thermometers. In the chamber they wore only cotton shorts and sandals.

Because of operational and other limitations on the numbers of men available for the experiments, subjects were required to work in all the experimental climates in succession. These were presented in balanced sequences to different groups of subjects in accordance with the letters in the arrays of a latin square design. The latin letters represented the climates and the columns of the design the experimental sessions.

The statistical significance of differences in the principal indices of performance was tested by an analysis of variance technique. The main terms in the analysis, climates, sessions and subject groups, were tested against a compound error term, a latin square residual.

Such a test of the effect of climates is justified, if it can be assumed that the three-way interaction between the main effects is zero. Adopting the randomization model of Wilk and Kempthorne (1956), the components of variance of the climates mean square may be written as error plus the interactions of subject groups with climates and with sessions plus the climates variance, and the components of the residual as error plus the three first order interactions. A test of the significance of the ' climates ' mean square against the latin square residual is then ' correct ' when the interaction variance of climates and sessions is zero. When this interaction is greater than zero, the test gives a conservative estimate of the significance of the climates variance.

The effects of conditions which occurred within every session were tested for significance either against a final residual error term, or against a significant interaction of the ' within session ' condition with subject-groups, climates or sessions. The levels of significance given in the following text refer generally to the appropriate ' F ' ratios in the analyses of variance given in the appendices to earlier unpublished reports (Pepler 1953).

§ 3. Manual Tracking, Experiment 1

The purpose of this experiment was to provide preliminary validatory evidence for the general conclusions of the earlier work by investigating the effect of differing climates on a tracking task broadly similar to that used in England, and to study the nature of any observed changes in performance in greater detail than was possible with the apparatus previously employed.

3.1. *Method*

Climates

Sixteen subjects worked in four indoor climates with the following dry and wet bulb temperatures 75°/65°, 85°/75°, 93°/83° and 100°/90°F, and with an average air movement of 80 ft/min. The basic effective temperatures of these climates were 66°, 76°, 84° and 91°F.

Apparatus

Four pursuitmeters were manufactured to specifications given by Dr. A. Carpenter of the Medical Research Council's Applied Psychology Research Unit and followed a design by Welford (1951). The pursuitmeter is a machine which imparts an erratic to-and-fro motion to a target and provides a second pointer opposite to, and movable in the same plane as the first, but controlled by the subject (Fig. 1). The subject controls his pointer by raising and lowering a handle which can be loaded by hanging weights upon it. Fundamentally these machines were similar in design to the pursuitmeters described in earlier papers (Mackworth 1950, Carpenter 1950) but they differed in the improved methods of scoring.

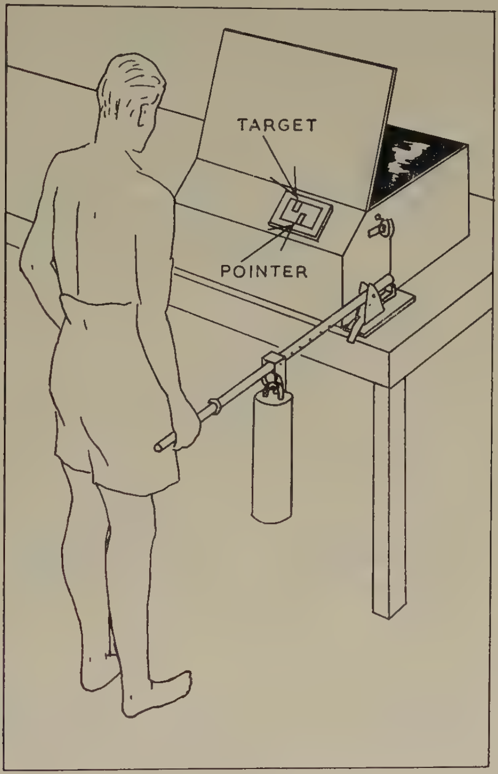

Figure 1. Manual tracking, a task of continuous pointer alignment.

In England errors of alignment were recorded in terms of the *relative* movement of the two pointers to each other. The principal improvement in the scoring system of the newer apparatus was the provision of a method of recording electrically the misalignment of the pointers occurring with and without relative movement, thus providing a total error score which is integrated for time. In this experiment advantage was taken of an additional refinement of the scoring system and the total error score was split up and recorded on separate scoring meters depending upon the relative position and movement of the two pointers. It was possible in this way to score separately errors due to the controlled pointer lagging behind the target from those due to its leading the target. Also, errors due to the controlled pointer swinging beyond or ‘ overshooting ’ the target could be scored separately from those due to the controlled pointer not swinging far enough or ‘ undershooting ’. These lags are referred to as ‘ errors of approach ’,

Procedure

Each subject had eight 15-minute runs during each session, one run on each machine with each of two different weights on the control handle. The weights were such as to produce loadings, measured at the subject's hand, of 8 and 24 lb. The average energy cost of the task was approximately 82 and 117 kg cal/m^2/hr. A five-minute rest was given between all the runs except the 4th and 5th when ten minutes were allowed, and the weights were changed on the four machines. The sequence in which subjects worked on any machine with each handle load was also varied every session so that each subject experienced each handle loading once on each machine during every session.

3.2. *Results*

The results are presented in two sections. The first section, dealing with the general effects of the experimental conditions on the accuracy of tracking, on body temperature and on the amount of sweating, is similar to and easily compared with the earlier Cambridge work. The second section consists of a more comprehensive analysis of the changes in the performance of this tracking task under the different conditions.

The general effects of the experimental conditions

The mean errors are shown in Table 1 where it will be seen that error rose sharply between 76° and 84° but was stable above and below these temperatures. These results are in close agreement with the work on artificially acclimatized men at Cambridge by Mackworth (1950) and Carpenter (1950) who found significant deteriorations in accuracy for similar tracking tasks when the basic effective temperature was raised from 76° to 86°F. The average final body temperature and average sweat loss rose steadily and significantly over the range of temperatures used, as shown in Table 2. Again the results were similar to those obtained in Cambridge. These findings are interesting in view of the very great differences between the conditions in which the experiments at Cambridge and Singapore were conducted, not only in the normal daily climate, but also in the subjects' general living and working conditions.

Table 1

Mean Error of Alignment at Each Level of Warmth

	Effective Temperature (°F)			
	66	76	84	91
Time and distance off target (in arbitrary units)	179	180	231	232

The standard error of the difference between means is 13, i.e. means differing by 26 or more are significantly different ($P < 0{\cdot}05$).

Table 2

Mean Final Body Temperature and Mean Total Sweat Loss at Each Level of Warmth

Effective temperature of room (°F)	66	76	84	91
Final rectal temperature (°F)	98·44	98·76	99·31	99·97
Total sweat loss (kg)	0·206	0·487	0·722	1·665

The significance of the differences between means was tested by the calculation of the statistic 't'. The values obtained for pairs of climates taken in order of increasing warmth were 16·9, 27·8 and 33·5 for rectal temperature, and 14·2, 3·6 and 8·8 for sweat loss. A 't' value as big or bigger than 2·8 is highly significant ($P < 0{\cdot}01$).

In order to test whether there was any direct relationship between rise in rectal temperature and increased error scores each subject was classified for each climate as being above or below the average for that temperature in respect of error score, and of final rectal temperature. The number of individuals falling into each of the four possible categories for each climate are given in Table 3. Clearly there was no significant association between performance and rectal temperature for the various room temperatures.

Table 3

Examination of the Association Between Error Score and Body Temperature

		Effective temperature of room (°F)							
		66		76		84		91	
Rectal temperature		+	−	+	−	+	−	+	−
Error score	+	3	5	4	3	4	3	4	4
	−	3	5	2	7	4	5	5	3

The entries in the cells are numbers of subjects. The symbol + means that the subjects listed were above the average of the group. The symbol − means they were below.

The effect due to practice over the four days of the experiment was not significant.

The fact that an improvement in the accuracy of performance was observed during the experiment in England but not in this one is due probably to differences in procedure. In this experiment the subjects worked for fifteen instead of three minutes at a time, and with no knowledge of their own performance scores.

No attempt was made to evaluate the effect of increasing the control handle load from 8 lb to 24 lb. The loads on each pursuitmeter machine were only changed half-way through a session and so their effect on performances was confounded with those due to differences between the first and second halves of a session.

An analysis of the changes in the types of error at different levels of warmth

It has been demonstrated that the accuracy of continuous pointer alignment is adversely affected by increased room temperature, but the question remains, ' In *what way* is behaviour affected by the warmer conditions to produce this decreased accuracy ? '.

On average the subjects failed to ' keep up ' with the demands of the task. Errors of ' persistent lagging ' contributed about 60 per cent of the total error score, while errors of ' overshooting ' and of ' leading ' each contribute about 17 per cent, and errors of ' approaching ' about 5 per cent. The actual proportion of the total error score contributed by each of the four types of misalignment in each climate, expressed as a decimal fraction, is shown in Table 4.

Table 4

The Proportional Contributions of Four Types of Misalignment to the Total Error Score at Each level of warmth

Type of Misalignment	Effective temperature of room (°F)			
	66	76	84	91
' Lagging '	0·617	0·613——	0·569——	0·597
' Leading '	0·161	0·166——	0·180——	0·155
' Overshooting '	0·173	0·169——	0·194	0·188
' Approaching '	0·049	0·051——	0·057	0·060

The connected pairs of proportions differ significantly ($P = < 0{\cdot}05$).

Although the *proportional* contribution of the errors of ' persistent lagging ' decreased at an effective temperature of 84°F, while other types increased, the *actual amount* of error due to persistent lagging did in fact increase as shown in Fig. 2.

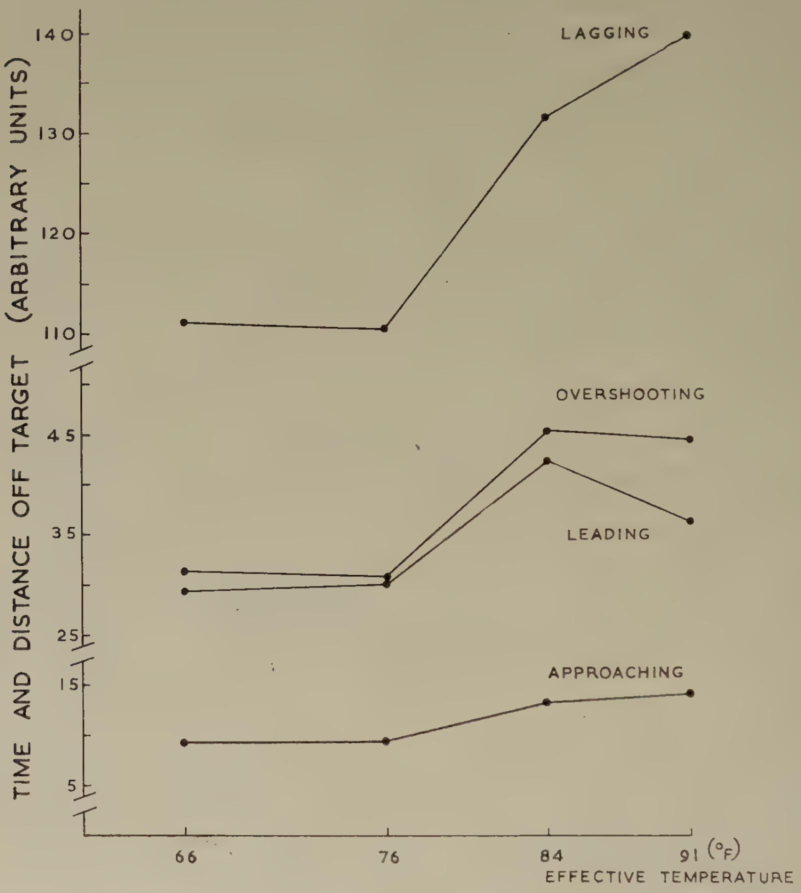

Figure 2. Effects of environmental warmth on the accuracy of pointer alignment in terms of four types of faulty tracking.

Each of the partial scores showed a highly significant increase when the effective temperature was 84°F as compared with 76°F. At the hottest climate of 91°F the errors due mainly to persistent lagging were significantly higher than at 84°F, while the errors of ' leading ' decreased significantly. The errors of ' overshooting ' and errors of ' approaching ' remained approximately unchanged. None of the four partial scores showed a significant change at the coolest climate of 66°F from that at 76°F.

It would appear that at an effective temperature of 84°F, as compared to 76°F, the subjects were making errors of alignment in both directions, and being slow to respond to the target changes. At an effective temperature of 91°F, however, the tendency to lag behind the display pointer increased greatly beyond that at 84°F, while the tendency to ' lead ' decreased.

§ 4. Manual Tracking, Experiment 2

A second tracking experiment was designed to provide a preliminary test of the Effective Temperature Scale (Bedford 1946) against performance criteria, by measuring performance in both a dry and a moist climate at each of the effective temperatures concerned. Opportunity was also taken to study the effects of different handle loadings.

4.1. *Method*

Climates

The eight climates in which the thirty-two subjects worked, were composed of four pairs, the members of each having the same effective temperature, but relative humidities of 80 per cent and 20 per cent respectively. The dry and wet bulb temperatures of each pair of climates were as follows: 79°/74° and 89°/64°; 85°/80° and 100°/70°; 90°/85° and 110°/75°; 97°/92° and 120°/85°F. Since the average air movement in the chamber was 80 feet per minute the basic effective temperature for each pair was 72°, 79°, 84° and 92°F.

Apparatus

The apparatus consisted of the four pursuitmeter machines used in the first tracking experiment, but with a new pattern of movement of the target having smaller excursions and a slightly slower speed of movement.

Procedure

The subjects were weighed nude and their rectal temperatures taken immediately before entering and after leaving the chamber. For the first hour of each session they remained seated, and read, talked, slept or listened to music played over the loud-speaker system. Unsalted water was provided for drinking and records kept of the amount drunk. Rectal temperatures were then taken again and the work period commenced. Sixteen 3-minute tracking ‘ runs ’ were given, one on each machine with each of four control handle loads of 8, 16, 24 and 32 lb. Rests of three minutes were given after every run except after the 4th, 8th and 12th when five minutes were allowed, during which time the experimenter changed the handle loading on each machine. The order in which the subjects worked on the four machines with each handle load was varied every work period according to prearranged designs so that the subjects worked with each handle load once on each machine during every session.

Subjects were encouraged at all times to carry out this tracking task as accurately as possible and as an added incentive each subject's score was read out after every run.

4.2. *Results*

The effects of climate on performance

When performance was analysed with respect to (*a*) the effective temperatures of the four pairs of climates, and (*b*) the difference in relative humidity within the pairs, it was found that only the difference in temperature had a significant effect ($P<0{\cdot}05$), although the effect of the difference in relative humidity was quite large and almost significant.

Errors increased significantly in the dry climates between the effective temperatures of 79° and 84°F, but between 72° and 79°F for the moist ones as shown in Fig. 3. Thus in this experiment the critical temperature range over which the accuracy of alignment deteriorated was lower for the moist than for the dry climates.

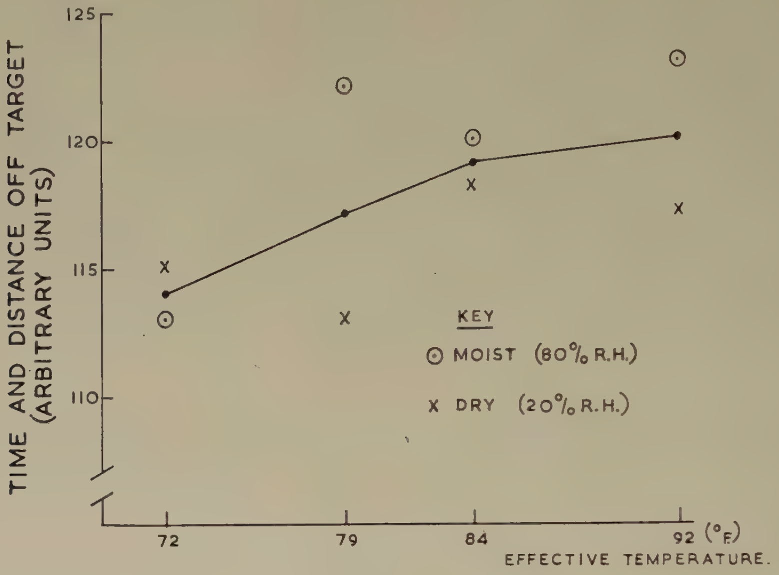

Figure 3. Effects of environmental warmth and relative humidity on the accuracy of manual tracking.

The effects of handle loading on performance

The error scores for different handle loadings are set out in Table 5. The 16 lb load was the optimum for accurate tracking, being significantly better than each of the other three loads. Performance with the 32 lb load was significantly worse than with any of the other handle loads.

Table 5

Mean Error of Alignment with Each Handle Load

	Handle loads			
	8 lb	16 lb	24 lb	32 lb
Time and distance off target (in arbitrary units)	117	112	117	126

The standard error of the difference between means is 2, i.e. means differing by 4 or more are significantly different ($P < 0{\cdot}05$).

The effect of the handle loadings varies in the different climates ($P < 0{\cdot}01$). At both levels of relative humidity the effect remained similar, but varied significantly ($P < 0{\cdot}05$) over the four levels of warmth. An inspection of the scores with each handle load at the four effective temperatures as set out in Fig. 4 shows that this significant interaction was due mainly to the performances with the 16 lb. and 32 lb. loads at an effective temperature of 92°F.

When tracking with the 32 lb load the subjects' accuracy was significantly worse than at 84°F, while with the 16 lb load it was better.

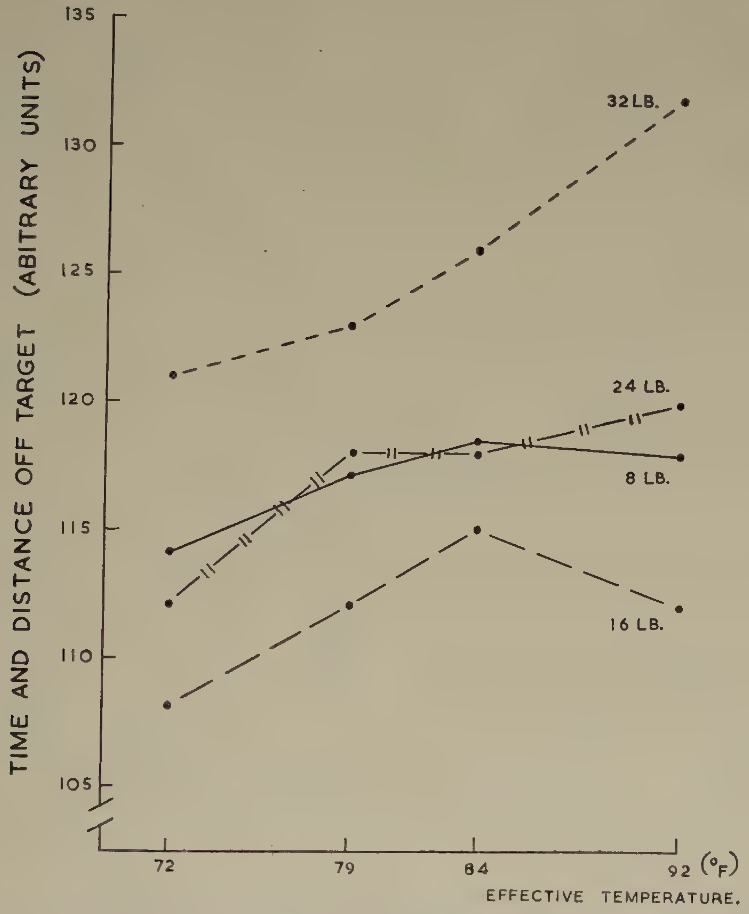

Figure 4. Effects of handle loading and environmental warmth on the accuracy of manual tracking.

The effects of practice on performance

Throughout the experiment subjects were encouraged to do their best and were provided with knowledge of results so that within most teams quite a strong spirit of competition developed. It is thus not surprising to find that the effect of practice over the eight sessions in the chamber was highly significant (Table 6).

Table 6

Mean Error of Alignment at Each Session

	Sessions							
	1	2	3	4	5	6	7	8
Time and distance off target (in arbitrary units)	161	136	126	114	108	102	101	94

The standard error of the difference between means is 4, i.e. means differing by 8 or more are significantly different ($P < 0{\cdot}05$).

The effects of climate on physiological reactions

Changes of body temperature and sweat loss for each climate and effective temperature are given in Table 7. The average final body temperature was significantly higher with each increased effective temperature. At the coolest and warmest effective temperatures, there was no difference between the average values in the moist and in the dry climates, but for the two intermediate ones the body temperature was significantly higher after work in the dry than in the moist climate. The average total sweat losses increased with each higher effective temperature and the difference between any pair of these values is significant. The sweat loss was greater in the dry than in the moist climates, but at an effective temperature of 92° this difference was not significant.

Table 7

Final Rectal Temperature and Total Sweat Loss for Each Climate and Effective Temperature

Relative humidity		Effective temperature of room (°F) 72		79		84		92
		Final rectal temperature in °F						
20 per cent		98·90		99·70		99·80		100·20
				×		×		
80 per cent		98·90		99·10		99·50		100·30
	Mean	98·90	×	99·40	×	99·65	×	100·25
		Total sweat loss in Kg						
20 per cent		0·417		0·881		1·240		1·790
		×		×		×		
80 per cent		0·199		0·340		0·580		1·620
	Mean	0·308	×	0·611	×	0·910	×	1·705

Values with a symbol × between them are significantly different ($P < 0{\cdot}01$).

If one considers the average values of both the performance and the physiological data at each of the effective temperatures a direct relationship would appear to exist between them, since as the environmental warmth increased body temperature, sweat rate and error scores also increased. However, if the values for each climate are compared, no such relationship is found. For example, performance was rather better in the dry climates.

Table 8

Distribution of Individuals at Each Climate with respect to Mean Error Score and Body Temperature

		Effective temperature of room (°F) 72		79		84		92	
Relative humidity 20 per cent									
Rectal temperature		+	−	+	−	+	−	+	−
Error score	+	7	6	6	6	8	6	8	6
	−	9	9	8	11	7	11	10	8
Relative humidity 80 per cent									
Rectal temperature		+	−	+	−	+	−	+	−
Error score	+	6	5	7	5	10	3	6	6
	−	10	10	6	14	8	11	9	10

The symbol + means that the subjects listed were above the average of the group. The symbol − means they were below.

while body temperature and sweat losses were greater in the dry than in the moist climate. A more precise test of a possible relationship between final body temperature and error score was carried out by classifying each subject as being either above or below the average in respect of each of these variables for each of the climates, so holding the climatic variables constant. The observed distribution of individuals in the four categories is shown in Table 8. Clearly there was some association between score and final rectal temperature, but it was found (by χ^2 test corrected for continuity) in no case to reach significance ($P > 0{\cdot}05$).

Subjective opinion on comfort and performance

After completing the eight sessions in the chamber each of thirty-one of the subjects filled in a simple questionnaire form covering his experience of the test.

Although five subjects said they found none of the climates uncomfortable, the remainder were agreed that the two with an effective temperature of 92°F were uncomfortable and interfered with tracking. Conversely, twenty-two of the subjects said they preferred the coolest climates and found them the easiest to work in. Thus over the extremes of the conditions experienced in the experiment there was a close agreement between the subjective and objective data, but not over the intermediate conditions although performance did deteriorate between these.

Twenty-two of twenty-seven subjects said they found it harder to work in the hot–moist climate than in the hot–dry one, but at the coolest climates only thirteen of twenty-one subjects said they found it easier to work in the dry than in the moist climate. This agreed with the replies to the direct question as to awareness of the difference in humidity—twenty-one noticed a difference, but of these fourteen said it was more noticeable in the hot climates than in the cool.

Twenty-four of the subjects preferred tracking with the 16 lb handle load (which was the load that yielded the most accurate performance). Seven subjects said they could manage the heaviest weight without finding the task very much more difficult, but twenty-four thought that the 24 lb load was their maximum.

4.3. *Discussion*

The results of this experiment were in general agreement with those obtained in earlier pursuitmeter experiments. In view of the widely differing backgrounds to the several experiments, of differences in apparatus and in experimental procedures occasioned by slightly differing approaches, agreement on the effect of increased temperature, of handle loads and of the inadequacy of the simple physiological measure as indicators of the accuracy of performance, is quite surprising. At the same time this experiment draws attention to the possibility that the identification of the range of effective temperatures over which performance deteriorates may depend partly upon the relative humidity of the climates used in the investigation.

In an experiment with a heavily loaded pursuitmeter Mackworth (1950) found a positively accelerated trend in the error curve when this was plotted against equal increments in temperature. In Carpenter's pursuitmeter experiment in England (Carpenter 1950) and in these experiments at Singapore the error scores appeared to become stabilized at a high level in the warmer climates. It had been thought that perhaps the error scores were approaching some maximum value imposed by the apparatus, but this was certainly not the case in the present experiment. The greatest error scores recorded were only about one-third of the maximum value possible and a tendency towards a progressive increase in error with increased warmth is apparent when only performances with the heaviest load are considered (Fig. 4).

§ 5. MANUAL TRACKING, EXPERIMENT 3

An experiment in England on artificially acclimatized men (Mackworth 1947, 1950), designed to study the relation between the effects of incentives and climatic stress, had shown that the output from a task requiring heavy physical effort decreased progressively with each increase in room temperature when the men worked under both low and high incentive conditions. Mackworth concluded that the adverse effects of high room temperature could not be offset by greater incentives. It was noted also that the deterioration in output had in fact been greater in the case of the best workers and in the case of performances under the high incentives. On the other hand, in an experiment on the reception of morse code messages (Mackworth 1946) it was the least efficient telegraphists whose performances were found to deteriorate the most at the higher temperatures. These two sets of findings, which at first appear contradictory, were taken as evidence that a climatic effect was most marked when an individual was already using his reserves of ' energy ' to the full, either by working hard at a task demanding heavy physical effort or by straining unsuccessfully to deal with a task requiring a high level of skill (Mackworth 1950).

The present experiment was undertaken to test whether (1) the effects of warm climates would be similar at two levels of incentive on a task which required skilled movements rather than physical effort, and (2) whether the effects of the warm climates would be greater when the subjects were working harder under high incentives or when their error scores were higher at a fast speed of working.

5.1. *Method*

Climates

Sixteen subjects carried out the task in four indoor climates with the following dry and wet bulb temperatures: 85°/75°, 90°/80°, 95°/85° and 100°/90°F and an average turbulent air movement of 100 ft/min. The mean temperature of the surroundings was approximately the same as the air temperature. The effective temperatures were 76°, 81°, 86° and 91°F respectively.

Apparatus

The apparatus consisted of the four pursuitmeter machines used in the previous experiments with the control handles weighted to produce a load of 16 lb (the optimal load in Experiment 2).

Procedure

Before the experiment all subjects had one week of intensive practice at the task under normal indoor conditions. They learnt to track the target at four different rates of change of direction of movement, approximately 0·2, 0·3, 0·4 and 0·5 c.p.s. On two days they worked with both low and high levels of incentives. When the subjects worked with low incentives they were asked to do the job as well as possible but thereafter received no other encouragement nor information on their performance. The high incentive condition included the provision of minimum standard scores to be exceeded if possible, and knowledge every minute of the score achieved together with appropriate praise and encouragement at the end of each three minute spell of work.

During the Test Sessions the subjects did the task for a succession of twenty 3-minute runs at two target speeds, 0·3 and 0·5 c.p.s. At each speed the subjects worked under the two incentive conditions. The target speeds alternated every five runs while the incentive conditions changed only after the tenth run, i.e. half-way through the session. After the fifth and the fifteenth runs a six-minute rest was given and the experimenter changed the speed of the cams driving the display pointers. After the tenth run a fourteen-minute rest was given, the display speeds were changed and the experimenter announced the changed incentive conditions for the second half of the session. Four-minute rests were allowed between all other runs. The sequence in which each subject experienced the four working conditions was varied systematically at each session.

5.2. *Results*

Since all the test runs were of equal length there was more opportunity for making errors at the higher speed than at the lower. The scores at the two speeds have therefore been analysed separately.

The effect of incentives

The two procedures under which the subjects worked, one giving no knowledge of success or failure and no special encouragement, the other using target scores, a knowledge of the scores achieved and praise and encouragement, produced significant effects ($P < 0{\cdot}05$) on the accuracy of the tracking. At both display speeds accuracy was better under the high than under the low level of incentive as shown in Table 9.

Table 9

Mean Errors of Alignment with Different Levels of Incentive

	Target speed	Incentive level	
		High	Low
Time and distance off target (in arbitrary units)	Fast (0·5 c.p.s.)	126	149
	Slow (0·3 c.p.s.)	64	80

The standard error of the difference between means at either speed is 5, i.e. means differing by 10 or more are significantly different ($P < 0{\cdot}05$).

The effect of temperature

The temperatures of the different climates again had significant effects ($P < 0{\cdot}05$) on the accuracy of tracking.

At each target speed the alignment of the pointers was most accurate in a climate with an effective temperature of 81°F, and was significantly worse when the temperature was both 76° and 86°F. At an effective temperature of 91°F performances were less accurate than at 81°F, but, at the fast speed, accuracy at 91°F was also significantly worse than at 86°F (Fig. 5).

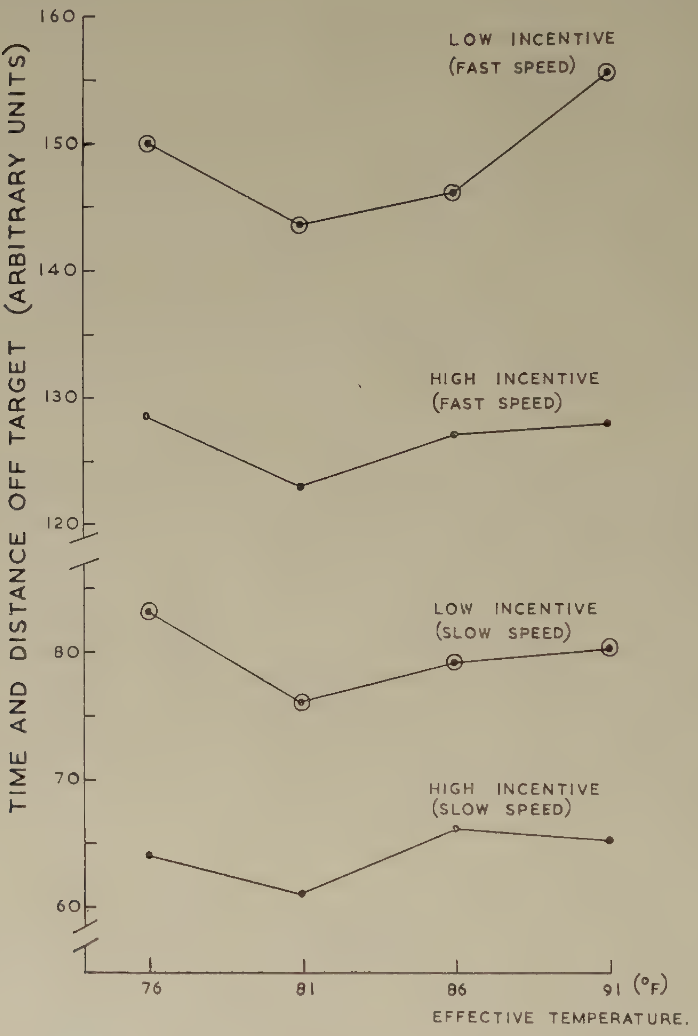

Figure 5. Effects of incentives, target speed and environmental warmth on the accuracy of manual tracking.

The most interesting finding was that at both speeds of working this climatic effect did not differ significantly under the two incentive conditions. There was no evidence that the effect of environmental warmth was proportionately greater either with the larger scores at the fast speed or when the subjects were making a greater effort under the high incentive.

Total sweat loss records

The average amounts of weight lost by the subjects during the three hours spent in each climate are given in Table 10.

Table 10

Mean Total Sweat Loss at Each Level of Warmth

Effective temperature of room (°F)	76	81	86	91
Sweat loss (kg)	0·349	0·517	0·663	1·056

The ' t ' values obtained for pairs of climates taken in order of increasing warmth were 7·7, 6·1 and 9·5. A ' t ' value as big or bigger than 2·8 is highly significant ($P<0{\cdot}01$).

The increases in sweat loss with each increase in warmth were all highly significant. There again appears to be no direct relationship between this physiological measure and the accuracy of tracking.

5.3. *Discussion*

The findings that the effects of the different climates on performances at each speed of working were similar under both the incentive conditions confirm Mackworth's results obtained with a task demanding heavy physical effort. The appearance of a climatic effect was independent of the procedures which were used to raise the subjects' level of performance, but the changes in performance under the different incentives at each climate were just as great as the changes between different climates for performances under the same incentives. In other words, the average error of alignment in the least favourable climate under the high incentives was no worse than it was in the most favourable climate under the low incentives.

Conversely, it can be said that the adverse climatic effects on the performances under the low incentive conditions were completely offset by the introduction of the higher incentives. This finding has important practical implications, since in every-day life the most likely need is for the maintenance of an arbitrary level of performance irrespective of climate. The evidence from both this and Mackworth's experiment indicates that for short periods of work and while exposed for two to three hours to an unfavourable climate, a man may sometimes maintain a level performance, which is equal to that for performances in the most favourable climate, provided the incentives to do the task can be increased sufficiently.

It was an interesting and rather surprising finding that the accuracy of performance in the cooler climate of 85°/75°F was worse with both levels of incentive than in a climate of 90°/80°F. In the two earlier experiments with this task at Singapore the average performances were better in a climate cooler than the ambient temperature. Why there should be this discrepancy between the results of the different experiments is not clear. One possible reason may however be in the relationship between warmth, incentive and practice. The subjects in the first two experiments had had no previous practice at the task as they had in this experiment. Also, they had worked with differing handle loads, and the overall conditions had been less favourable to the maintenance of a high level of interest. It seems possible that the cooler climate stimulated poorly motivated and untrained subjects to better performances, but interfered with the performances of well motivated and practised subjects. Deteriorations of accuracy in climates both warmer or cooler than that of 90°/80°F suggest that the present subjects were adjusted to a small range of temperature variation about this climate with an effective temperature of 81°F. Since they had been living for at least six months in a stable tropical climate, with a very similar average effective temperature, such an interpretation seems reasonable.

§ 6. Visual Watch-keeping Experiment

An experiment performed in England (Mackworth 1950) showed that the number of signals missed at a task requiring prolonged vigilance to detect small signals increased when the effective temperature was approximately 10°F above or below the control effective temperature of 76°F. A further experiment was accordingly undertaken in Singapore using the same task. It should be noted that whereas the pursuitmeter experiments provided sensorimotor tasks in which control action involving considerable physical effort was required, the present task was essentially 'mental' in character, the motor component being very small.

6.1. *Method*

The apparatus and the procedure for each session were essentially the same as described by Mackworth (1948, 1950). A subject sat alone in the chamber

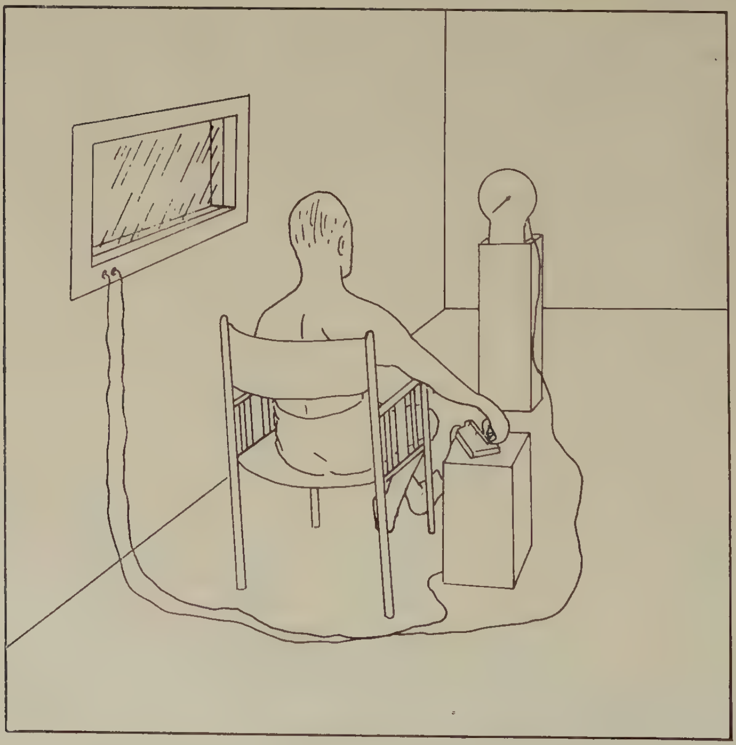

Figure 6. Visual watch-keeping, a task of prolonged vigilance.

for two hours during which time he had to remain alert to observe small infrequent changes in a visual display occurring at apparently irregular intervals. The display consisted of a black pointer against a uniformly white vertical background. The tip of the pointer moved in a ten-inch circle by a succession of equal-sized movements or jumps, one jump occurring every second and a hundred completing one circle. The change in the display was a jump of twice the usual size which had to be responded to by pressing a morse key. The display was placed at eye level eight feet in front of the subject, and illuminated by four fluorescent tubes mounted near the ceiling of the chamber (Fig. 6).

Eighteen naval ratings carried out the task in three artificial climates with dry and wet bulb temperatures of 75°/65°, 90°/80°, and 120°/85°F.

The average air movement was 80 ft/min, and the effective temperatures of these climates were 67° 82° and 92°F respectively.

Three subjects were tested each day for three consecutive days, working in a different climate on each day. The time of day at which the test was given was constant for each subject.

6.2. *Results*

Incidence of missed signals

The average number of signals missed in the moderately warm climate of 90°/80°F, (with an effective temperature of 82°F) was significantly less than in either the cooler climate of 75°/65°F or the warmer one of 120°/85°F (with effective temperature of 67° and 92°F respectively). The figures are set out in Table 11.

Table 11

The Effect of Environmental Warmth on the Detection of Signals During Visual Watch-keeping

	Effective temperature of room (°F)		
	67	82	92
Mean number of Missed signals (Max. possible = 48)	13·5	9·4	13·4

The standard error of the difference between the means was 1·4, i.e. means differing by more than 2·8 were significantly different ($P < 0{\cdot}05$).

The variability attributable to the differences in performance in each half-hour of a work period was highly significant ($P < 0{\cdot}001$). It can be seen from Table 12 that the mean number of signals missed in each half-hour increased

Table 12

The Effect of Duration of Watch on the Number of Signals Missed

Half-hours	1st	2nd	3rd	4th
Mean number of missed signals (Maximum possible per ½hr = 12)	1·8	3·1	3·6	3·7

The standard error of the difference between means was 0·28, i.e. means differing by 0·56 or more were significantly different, ($P < 0{\cdot}05$).

progressively from the first to the last. The results in respect of both climate and length of work period thus essentially confirm those obtained with the artificially acclimatized men in England.

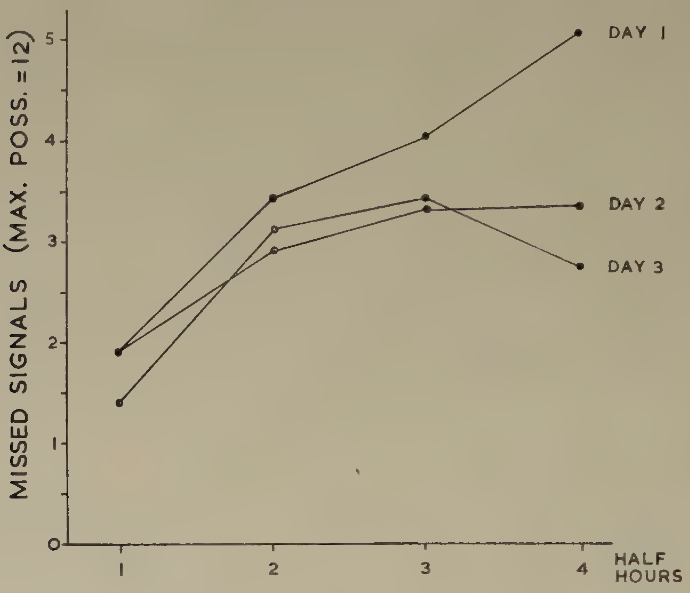

Figure 7. Number of signals missed during each half-hour of visual watch-keeping on successive days.

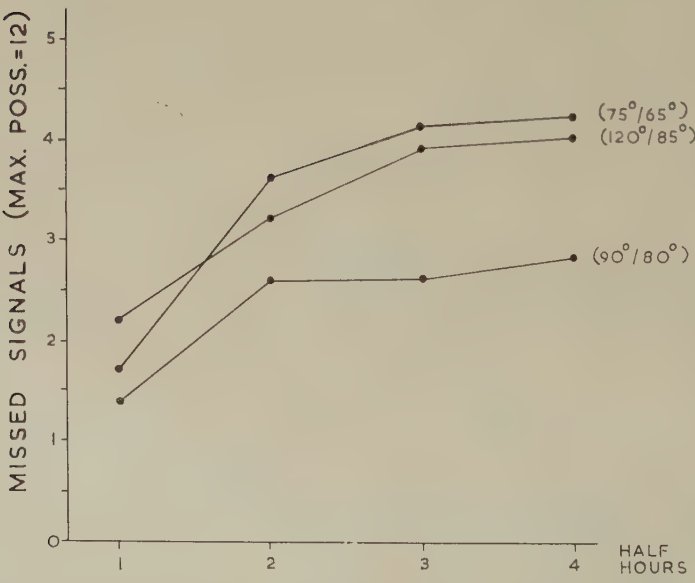

Figure 8. Number of signals missed during each half-hour of visual watch-keeping in different climates.

The marked deterioration in performance after the first half-hour of the work period occurred in each of the climates, and on each day of the experiment, although the variability in this effect on the different days was almost significant (Fig. 7). The average number of signals missed decreased over the three days of this experiment ($P < 0{\cdot}05$). Inspection of Fig. 7 shows that this was due principally to a progressive reduction in the number of signals missed during the last half-hour of the two-hour watch period.

The average number of signals missed in each half-hour of the watches in the three climates did not depart significantly from the general trend in performance during a watch. But inspection of Fig. 8 suggests that the deterioration in efficiency during the second half of a watch tended to be greater in the cooler and warmer climates than in the intermediate one of 90°/80°F.

Physiological observations

The averaged values of final rectal temperature and total sweat loss are given in Table 13.

Table 13

Mean Final Rectal Temperature and Mean Total Sweat Loss at Each Climate

	Effective temperature of room (°F)		
	67	82	92
Final rectal temperature (°F)	97·98	98·52	99·76
Total sweat loss (kg)	0·161	0·266	1·011

The ' t ' values obtained for pairs of climates taken in order of increasing warmth were 3·7 and 10·5 for the mean final rectal temperatures, and 3·3 and 15·8 for the mean total sweat losses. A ' t ' value as big or bigger than 2·8 is highly significant ($P < 0{\cdot}01$).

The average final rectal temperature and total sweat loss increased significantly with each increase in room temperature. It would appear, from the equal deterioration in performance that occurred at both the cooler and the warmer climate, that there was no direct association between the changes in performance and these simple physiological measures.

§ 7. HIGH SPEED DECISION TAKING

In this experiment an investigation was made of the effect of warmth on a type of mental work very different from visual watch-keeping. The previous experiment made very small demands on the subjects' mental capacities. However, under such conditions failures in attention increased during work, and unusual levels of warmth appeared to have accentuated this trend. A study of the effect of warmth on a task imposing a much greater mental load seemed desirable.

A novel task which required subjects to respond rapidly to ever-changing complex visual material was chosen for the present experiment. The task taxed a subject's capacity to make the appropriate responses by limiting the time during which he could perceive and organize the available data. This task was chosen in order to extend the research to include a mental skill involving a form of ' speed stress ' which was receiving considerable attention from other workers at that time (Conrad 1951), and which possessed characteristics common to a number of the control and communication situations met in real life.

7.1. *Method*

The apparatus presented a series of twenty small cards for comparison with another set of ten similar cards. The former set of cards were spaced irregularly on a vertical belt, which moved at controlled speeds between pairs of the stationary cards mounted on each of five horizontal black bands, also unequally spaced (Fig. 9). The moving belt also carried eight cardboard shields mounted across the belt between and, in five cases, partly under the cards. The shields were large enough to cover the pairs of cards on the stationary display as they passed over them.

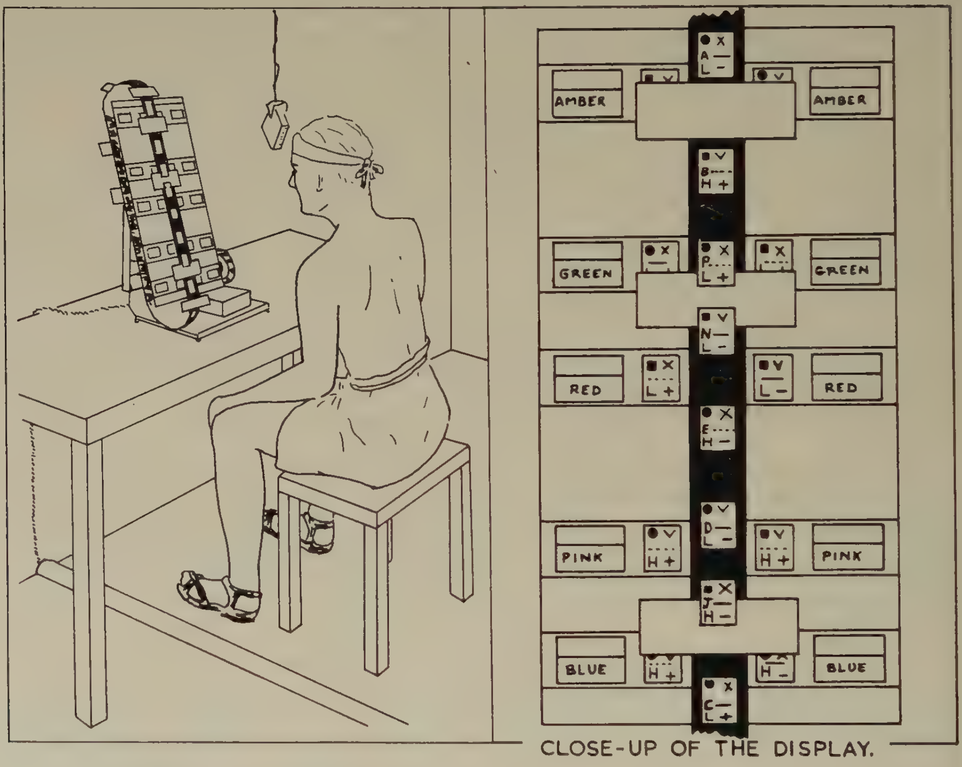

Figure 9. High speed decision taking, a complex mental task.

The task was to compare the six symbols on each of the cards on the moving belt as they approached and crossed the horizontal bands, with the six symbols on each of the stationary cards, and to report the number of differences between them. The shields on the belt affected the sequence in which the comparisons could be made by forcing the subjects to compare some cards in advance of crossing a band, and causing the comparison of others to be delayed until a crossing was already in progress. In many ways the task resembled a later version reported by Mackworth and Mackworth (1956).

The subjects were instructed to give their answers in a standard form: firstly, to identify the moving card by its alphabetical ' call sign ', then the stationary card by the colour reference of its band, and by its position to the right or left of the moving belt. No comparisons were to be attempted after a card had completely crossed a band, and so the subjects were advised to watch all the bands, in order to decide which of the possible sets of comparisons was the most urgent—in the sense of being available for the least time, and to deal with that one first.

During each experimental session the task was performed three times with the belt moving at a slow, medium and fast speed. The average time per comparison at these belt speeds were 8, 6, and 4 sec respectively. Since there were 200 comparisons to be made, each run lasted 26 min 40 sec, 20 min and 13 min 20 sec respectively.

Procedure

Twenty-four subjects first had the task demonstrated to them, and then on the day before the first experimental session they received detailed instructions, and did the task once at each of the three speeds.

Six subjects were tested separately on each of the four experimental days; the time of day remaining constant for each subject. Subjects sat at a comfortable reading distance before the apparatus with the centre of the stationary display approximately at eye level. A microphone relayed the subjects' responses to the experimenter in the observation room (Fig. 9). The display was illuminated by indirect light from the observation room, and by a 100 watt bulb suspended above the subjects position. This light also served as a ' ready signal '.

The subjects' responses were checked by the experimenter as right or wrong on a prepared answer sheet, and totalled for each man. The total number of comparisons which each failed to make was also recorded, as ' errors of omission '.

The subjects did the task at the three speeds every session, the order being determined each session from different random series of numbers. Four-minute rests were allowed between the three spells of work so that each session lasted for about 80 minutes. No immediate knowledge of results was provided, but subjects were encouraged to inspect the graph of their previous days total scores and they all showed great interest in their performances.

Climates

The subjects worked daily once in each of four indoor climates with dry and wet bulb thermometer readings of 85°/75°, 90°/80°, 95°/85° and 100°/90°F and an average speed of air movement of 100 ft/min. The basic effective temperatures of the climates were 76°, 81°, 86° and 91°F respectively. The order in which the climates were presented was changed each week, so that over the whole experiment all the climates occurred once only at each position in the sequence.

7.2. *Results*

No moving cards were over the stationary display at the start of a spell of work so that the rate of working increased until the display became ' loaded ' with moving cards, then remained approximately constant until towards the end when the rate of working decreased as the last moving cards began to cross the horizontal bands. A second variable factor which occurred at the start and finish of the test was that most subjects learnt one or two of the comparisons.

In order to eliminate the effects of these variable conditions at the start and finish of each trial, only the subjects' responses to an arbitrary sample of one hundred possible comparisons in the middle of the task were analysed, i.e. all comparisons of the sixth to the fifteenth (inclusive) of the moving cards with each of the ten stationary cards.

The principal source of error at all three speeds and in all the climates was a failure to make the comparisons: the number of faulty comparisons was relatively insignificant. Both, however, were analysed.

Effect of decision time

There was, as shown in Table 14 a very substantial ($P < 0{\cdot}001$) difference in the number of omissions between the different speeds of presentation. More than twice as many comparisons were missed when there was an average of 4 instead of 8 seconds for each of the possible comparisons. The differences in the presentation speeds must therefore have had little effect on their actual rate of working. In fact inspection of Table 14 shows, that when the presentation speed was doubled, the number of comparisons which the subjects attempted per minute increased by only about one-sixth.

Table 14

The Effects of the Time Allowed Per Comparison on the Performance of a High Speed Decision Taking Task

	Time per comparison		
	Slow (8 sec)	Medium (6 sec)	Fast (4 sec)
Omissions (per 100 signals presented)	23·3	36·4	54·8
Errors (proportion of responses made wrongly)	0·048	0·057	0·065
Comparisons per minute	5·8	6·4	6·8

The accuracy with which the subjects made the comparisons decreased significantly at the medium and fast speeds ($P < 0{\cdot}05$). When the speed of presentation was doubled the proportion of wrong comparisons increased by about a quarter.

Effect of climate

The average number of comparisons missed, and the proportion of comparisons wrong at each speed at each level of warmth are shown in Fig. 10.

The differences between the numbers of omissions in the four climates at the medium and fast speeds were smaller than at the slow speed, and might have been due to chance. Only at the slow speed did the warmth of the climates have a significant effect on the number of omissions made ($P < 0{\cdot}05$). The least number of comparisons were missed in the moderately warm climate with an effective temperature of 81°F, and more in both the cooler and warmer climates. Once again we find that the optimum climate was the one most similar in warmth to the normal indoor climate of Singapore.

The proportions of wrong comparisons did not suffer significantly in the four climates at the slow and medium presentation speeds, but only at the fast speed ($P < 0{\cdot}05$). At this speed a significant difference in the numbers of mistakes occurred in those climates which were at least 10°F apart.

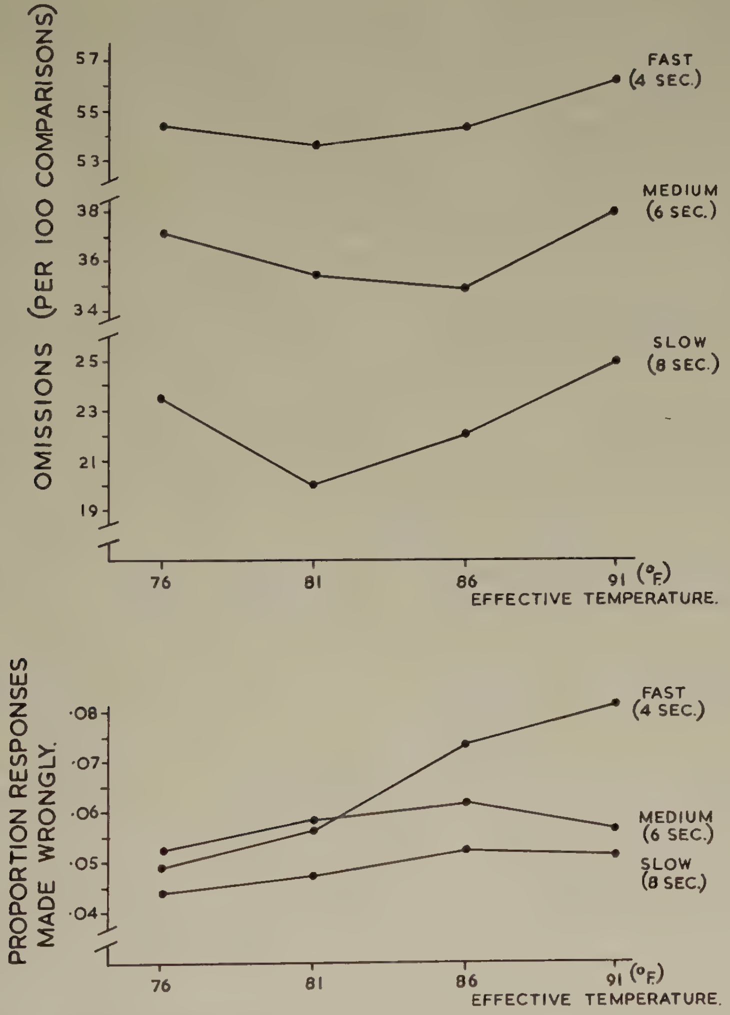

Figure 10. Effects of environmental warmth and time per comparison on high speed decision taking.

7.3. *Discussion*

Although these results showed a small but significant relationship between climate and performance, they did not fulfil the expectations with which the experiment was started, namely that the effects of increased speed of presentation would be disproportionately greater at high temperatures than at lower. However, it is possible to question their value as evidence against this hypothesis, on the grounds that conditions other than speed had varied also.

Three possible factors may be mentioned:

(i) It is possible that the differences in speed at which cards were presented may have changed the incentive value of the task. The subjects may have been more highly motivated at the fast than at the slow speed and consequently been less distractable.

(ii) The nature of the task almost certainly differed at the extreme speeds, and was in fact more complex at the slow than at the fast speed. A subject could have achieved a good performance at the fast speed by merely responding as quickly as possible to the comparisons as they became available, while at the slow speed he had to recognize the relative urgencies of several comparisons simultaneously available, and deal with them in the best possible sequence.

(iii) At the fast speed, rate of speaking may have provided subjects with an indirect indication of their level of performance and thereby enabled them to maintain a fairly consistent number of comparisons over the different experimental sessions—although at the cost of a loss of accuracy in the two warmer climates.

§ 8. Concluding Remarks

The results of the experiments at Singapore, on men who had been living in the tropics for over six months, and who had thus become acclimatized naturally to a warm humid atmosphere, confirmed to a quite remarkable degree the principal findings of experiments in a temperate climate on men who had been acclimatized in the laboratory to an abnormally warm climate.

The skilled performances of naturally acclimatized men were found generally to deteriorate over the same region of the temperature scale as did the performances of artificially acclimatized men, i.e. between climates with dry/wet bulb temperatures of 90°/80°F and 95°/85°F with an average air movement of 100 ft/min. The revised effective temperatures of the ‘ critical region ’ given by Mackworth and identified by the Singapore experiments are 81°F and 86°F. There was some evidence that manual tracking deteriorated over a lower range of effective temperature when the indoor atmosphere was humid than when it was dry.

Performances of a complex mental task and a well practised tracking task at Singapore were worse in climates which were only 5°F cooler than the normal tropical conditions. Artificially acclimatized men in England appeared less sensitive to the disturbing effect of cool conditions. This may possibly suggest that people living in temperate climates who have been acclimatized to heat still retain a tolerance of cool conditions which is lost during continued residence in the tropics.

The present results were obtained under special conditions and should not be regarded as evidence unfavourable to current air conditioning practice. The subjects were accustomed to living in a warm humid climate which hardly ever changed, and they worked in the cool condition for only one short period. Repeated or prolonged exposures to the cool climate might have resulted in an adaptation to a new range of temperature variation and an improvement in performance in the cool.

The adverse effect of an unusually warm atmosphere on manual pursuit tracking was independent of the special incentive procedures of ‘ knowledge of results ' and encouragement. The ' critical zone of temperature ' was the same when the men worked with such high incentive conditions or with ordinary low incentives. But the men at Singapore worked better in the warmest climate with high incentives than in the most favourable climate with low incentives. It therefore seems possible that a man's proficiency may sometimes be maintained at its normal level in a warm climate provided his incentive for the task can be increased sufficiently.

Confirmation was obtained also of the finding from previous experiments in England that the changes in skilled performance and body temperature which occurred with increased environmental warmth were not directly related. A similar indirect relationship was found also between changes in performance and the amount of weight lost as sweat during an experimental period.

The above experiments were conducted at the Medical Research Council's Royal Naval Tropical Research Unit, Singapore, from 1949 to 1952.

The writer would like to acknowledge his great debt to the British Royal Navy, and in particular to Surgeon-Commander F. P. Ellis, O.B.E., R.N., then Director of the Tropical Research Unit, for the excellence of the research facilities and for much personal help.

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On décrit une enquête par expériences à Singapore sur les résultats de l'assujettissement à des températures de milieu inusitées pour la compétence, dans des tâches de dexterité, de jeunes Européens domiciliés sous les tropiques.

Il s'agit trois expériences avec le tracement manuel, une avec la surveillance visuelle prolongée, et une avec une tâche où il fallait prendre des décisions au maximum de vitesse.

En générale, on a vu se confirmer les résultats les plus importants des expériences précédentes sur des hommes qui avaient été acclimatés artificiellement à la chaleur. Le rendement dans les tâches commença a détériorer dans la région de 27°c à 30°c sur l'échelle de température effective mais il y eut quelque raison de croire que la région critique était plus basse dans le cas des climats chauds et humides que dans celui des climats chauds et secs. Les hommes à Singapore paraissaient plus incommodés par les climats d'une fraîcheur inusitée que les hommes qu'on avait acclimatés artificiellement à la chaleur en Angleterre.

Es wird über einige Untersuchungen berichtet, die in Singapur über die Wirkung ungewohnter Höhe der Umgebungstemperatur auf die Leistungen junger in den Tropen lebender Europäer bei Geschicklichkeitsaufgaben durchgefürt wurden. Der Bericht betrifft 3 Versuche über Folgebewegungen der Hand, einen Versuch über lang-fortgesetztes visuelle Ueberwachen und einen Versuch über rasches Sich-Entscheiden. Grundsätzlich wurden die Hauptbefunde früherer Untersuchungen an künstlich hitze-akklimatisierten Männern bestätigt. Die Leistungen begannen zwischen 27°c und 30°c der effektiven Temperaturskala nachzulassen, wobei die kritische Region wahrscheinlich für feucht-warmes Klima tiefer lag als für trocken-warmes. Die Männer in Singapur schienen durch ungewöhnliche kühles Klima stärker gestört zu werden als künstlich akklimatisierte Männer in England.

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EFFECTS OF ELEVATED TEMPERATURES ON PERFORMANCE OF A COMPLEX MENTAL TASK

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Eleven subjects were tested on a complex mental task during one-hour exposures to four different dry bulb/wet bulb temperature conditions: 85°/75°, 90°/80°, 95°/85° and 100°/90°F. In a second experiment, ten subjects were tested at 85°/75°, 90°/80°, 110°/90° and 120°/90°F. In both experiments, differences in performance among the temperature conditions were small and not significant.

Introduction

It has been said that the prime limitation of a number of existing and design-stage manned aircraft is the tremendous increase in temperature associated with hypersonic speeds. This is also a problem with systems designed to operate beyond the earth's atmosphere, especially as regards the problem of re-entry. Solutions to the problems of structural heating seem to be in the offing, but what about the human element of the system? Refrigeration can be provided for the operator, but the weight penalty may soon become excessive. The important question thus seems to be, " How closely must we approximate room temperatures in order to assure adequate performance of the crew members ? "

Before we can attack this question, we must first decide what type or types of functions the individual will be expected to serve in these advanced weapon systems. It seems clear that his primary function will be to monitor instruments and displays, to inter-relate the information thus obtained, and to then make decisions as to the necessary courses of action to be followed relevant to the success of his mission.

Pepler (1953 a) has used a 'Complex Mental Task'—devised by Mackworth (1950)—in an attempt to measure the effects on performance of moderate deviations from normal temperatures, the range of effective temperatures being from 76° to 91°F. Under the conditions of his experiment, Pepler reported a significant decrement in the ability of his subjects to perform the type of mental activity involved with temperature deviations as small as 5° in either direction from an optimum effective temperature of about 81°F. In a subsequent application to another type of situation (involving sleep deprivation) the present author (Chiles 1955) was led to believe that the variability within, as well as between, subjects on this task was too large to yield significance for the actual order of magnitude of the differences which Pepler found.

Pepler has reported another experiment (1953 b and 1958) using this same task under the same temperature conditions, but in this second experiment he varied the incentive conditions (knowledge of results and encouragement) as well as the speed at which decisions were required. In this instance he states that the results show that temperature has a significant effect on the performance of the subjects.

Because of the importance of this type of problem, it was felt that the basic elements of Pepler's study should be repeated. The purpose of this report is to describe such a repetition which has been carried out in the all-weather chamber of the Aero Medical Laboratory.

EXPERIMENT I

Apparatus and Procedure

Subjects : The eleven subjects tested were male students at the University of Dayton. All were volunteers and were paid for their services.

Apparatus : The apparatus (see Fig. 1) was essentially that described by Pepler (1953 a). Briefly, a series of twenty small cards ($\frac{7}{8}$ in. × $1\frac{3}{8}$ in.), photographically reproduced on a closed loop of film, was presented to the subject

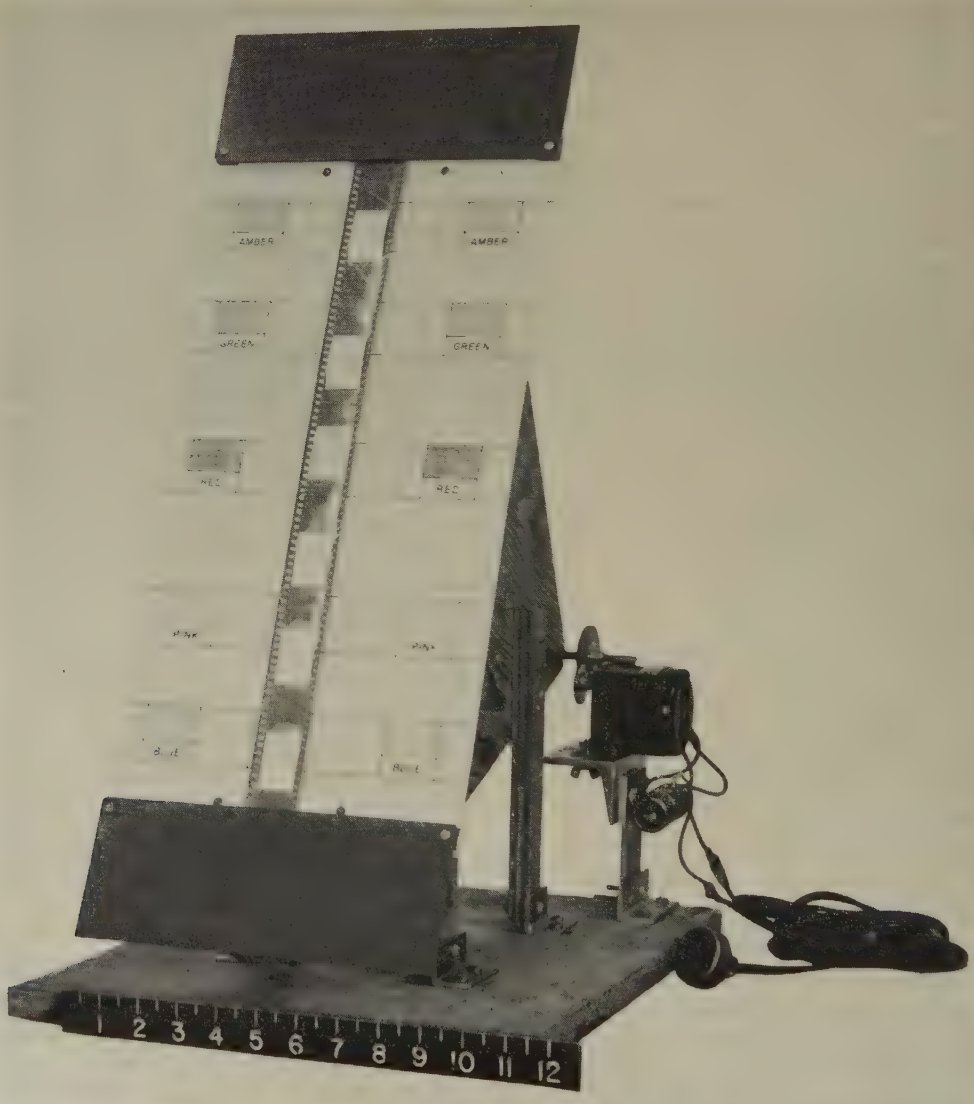

Figure 1. Subject's view of apparatus.

as the film loop rotated. The subject's task was to compare each of the twenty moving cards with each of ten stationary ones with respect to the number of differences between the set of symbols on the moving card and the stationary card. In a given location on each card there appeared one of two symbols, e.g., in the upper left corner would be found either an X or an O, at the left centre an H or an L, etc. (see Fig. 2). For a particular comparison of a moving with a stationary card, there were six such symbols to consider. Thus, the correct response would range from *six differences* if the cards had no symbols in common to *zero differences* if the cards were identically marked.

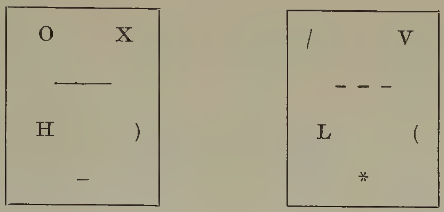

Figure 2. Sample of the stimulus cards used. These cards represent the case of six differences.

The separations between successive cards on the film strip were varied randomly, and the distances between the pairs of stationary cards were irregularly chosen. Thus, since the subjects were permitted to make a comparison only while the bottom edge of the moving card was below the top edge of the stationary card, the actual time available for making comparisons varied from time to time. For example, if the distance between two successive moving cards was rather large, the subject would be able to carry these two cards through several comparisons with stationary cards before the second moving card even appeared on the display ; on the other hand, if the two successive cards were close together, the subject would have to be careful that the second card did not pass a pair of stationary cards before he came back to it.

The speed of movement of the cards was such that decisions were required at an average rate of one per each 5·4 seconds. The total time for a session was approximately 25 minutes, the actual performance lasting approximately 18 minutes.

There were two primary differences between the apparatus used here and that used by Pepler. First of all, the actual symbols used were slightly different ; the present experiment employed symbols readily obtainable on a standard typewriter, whereas Pepler's symbols included some geometrical figures (squares, etc.). The second and probably more important difference was the fact that Pepler attached shields to the moving part of the display in such a way that the stationary cards were from time to time obscured. These shields were not used in the present study since, first of all, it would be difficult to describe in satisfactory terms just how they affected performance as the situation progressed and, second, the positioning of these cards was not indicated clearly in the Pepler report which precluded exact comparability between Pepler's experiment and the present study. Pepler used three speeds of presentation of comparisons (4, 6 and 8 seconds per comparison) in his first experiment and two speeds (3 and 6 seconds) in the second experiment. In the present study, only one speed of presentation was used, i.e. 5·4 seconds per comparison.

The experimental portion of the study was carried out in the Aero Medical Laboratory all-weather chamber which is a room 20 ft square and 8 ft high. Four different dry bulb/wet bulb readings were used: 85°/75°, 90°/80°, 95°/85° and 100°/90°F, and the wind velocity was approximately 100 ft per minute. These temperature and wind combinations yielded effective temperatures of 76°, 81°, 86° and 91°F respectively.

Procedure: The subjects were given four training trials before the main part of the experiment began. Each then received four test trials in the all-weather chamber. They wore shorts under each of the experimental conditions.

The subjects reported for the experiment three at a time with the exception of one group which contained only two subjects. The groups were treated as follows: upon reporting at the chamber, the first subject was placed in the chamber for a period of 30 minutes to acclimatize. At the end of this 30 minute period he began to perform the test, and the second subject entered to acclimatize. When the first subject had completed the test the second subject began performance and the third subject entered the chamber, etc. When the third subject had finished the test, the temperature of the chamber was shifted to the next experimental value and the procedure was repeated. On a given half-day the subjects went through two temperature conditions; they returned for their second half-day of testing at the same hour that they had reported for the first day's testing. Thus, six of the subjects were tested in morning and five in afternoon sessions. The total time in the chamber for a given subject was approximately one hour for each temperature condition.

The subjects were divided into four groups (three groups of three subjects each and one group of two subjects), each group receiving the temperature conditions in a different order. Group I was tested in the order 76°, 81°, 86° 91°; Group II in the order 81°, 86°, 91°, 76°; Group III in the order 86°, 91°, 76°, 81°; and Group IV in the order 91°, 76°, 81°, 86°; this procedure balanced the effects of learning in making the temperature comparisons.

For a particular test, the subject was seated before the apparatus, the film strip was placed in motion, and the subject read his answers into a microphone which was connected through an amplifier to a speaker outside the experimental room. The experimenter sat outside a window, through which he could observe the subject inside the chamber, and recorded the responses as they were given.

RESULTS

The results which are of primary interest are those which have to do with the effect of temperature on the performance of this task. These results are presented in Table 1.

Table 1

Omission and Error Data under each Temperature Condition

	Temperature			
	85°/75°	90°/80°	95°/85°	100°/90°
Omissions (mean)	37·7	34·6	37·1	39·8
Errors (mean)	10·0	10·4	11·3	10·8
% Errors	6·6	6·8	7·5	7·3

It can be seen in Table 1 that the differences among the various temperature conditions are not very large whether they are measured in terms of omissions or in terms of errors.

The data which reflect the learning trend are of less importance although they are of considerable methodological interest. These data are presented in Table 2.

Table 2

Learning Data

	Sessions			
	1	2	3	4
Omissions	45·3	39·5	33·5	31·1
Errors	11·4	10·7	9·0	11·4

The data show an orderly decrease in the number of omitted comparisons. On the other hand, although Table 2 shows evidence of a trend in the error data, this trend is reversed in the fourth session.

An analysis of variance, which is summarized in Table 3, was performed on the omissions data presented in Tables 1 and 2. This analysis showed that *the only* significant effect was that of sessions (learning), the remainder of the F-ratios being less than 1·00.

The overall results, then, show (a) that there was apparently no effect of the different temperatures on performance and (b) that the learning continued to progress throughout the four test trials.

Table 3

Summary of Analysis of Variance* of Omissions Data

Source	d.f.	SS	MS	F	P
Between subjects	11	22684	1890		
Temp. × Sess. (b)	3	6161	2054	<1·00	
Error (b)	7†	16523	2360		
Within subjects	32†	4433	137		
Sessions	3	1384	461	3·91	0·025
Temperatures	3	97	32	<1·00	
Temp. × Sess. (w)	6	598	100	<1·00	
Error (w)	20†	3354	118		
Total	43†	27117			

* Lindquist Type II design (1953). † Corrected for missing subject.

EXPERIMENT II

Apparatus and Procedure

Subjects : The ten subjects tested in the experiment were again male students at the University of Dayton. All were volunteers and were paid for their services.

Apparatus : This was the same as that used in Experiment I.

Procedure : The subjects were given six training trials before the main part of the experiment began. The experimental sessions were conducted in the Aero Medical Laboratory all-weather chamber, with the subjects wearing shorts at all temperatures.

The same sort of adaptation procedure used in Experiment I was used in this experiment. Each group of subjects experienced only one temperature condition on a given day. Successive experimental sessions were spaced one week apart with the exception that approximately three weeks elapsed between the second and third.

Group I (five subjects) experienced the following temperatures in the order: 85°/75°, 110°/90°, 90°/80° and 120°/90°F. These correspond to effective temperatures of 75°, 94°, 81° and 98°. Group II (five subjects) was tested in the order 110°/90°, 85°/75°, 90°/80° and 120°/90°F. Group III was run only at 120°/105°F (an effective temperature of 109°) although there were originally five subjects in this group, only three of them actually completed the session as will be explained later.

RESULTS

The performance data are presented as a function of temperature in Table 4. It can be seen from this Table that the differences among the various temperature conditions were again relatively small whether they are measured in terms of the number of comparisons which were omitted, i.e. not made, or in terms of the number of errors committed on the comparisons which actually were made. As is suggested by the magnitude of the differences, analyses of variance showed no temperature effect.

Table 4

Omission and Error Data under each Temperature Condition

	Temperature				
	85°/75°	90°/80°	110°/90°	120°/90°	120°/105°*
Omissions					
Mean	29·6	29·8	30·6	27·1	22·0
S.D. mean	7·7	8·2	8·3	9·3	—
Errors					
Mean	6·6	5·5	6·9	6·7	16·3
S.D. mean	0·82	0·79	0·92	1·4	—

* Three subjects only.

During the run two of the subjects in Group III (120°/105°) asked permission to discontinue performance—one subject after about five minutes, and the other after ten minutes. Both subjects gave feelings of nausea as their reason.

DISCUSSION

From the methodological point of view, the learning data from Experiment I indicate that on this task it is necessary to either balance practice effects or to provide adequate preliminary training in order to eliminate the possibility that the main effects will be over-shadowed by learning effects. Fortunately, the balancing does permit unbiased tests of the main effects of temperatures.

As was pointed out earlier, Pepler found significant differences with changes in temperature of 5°F. The results of the present experiment, in which no difference was found with changes in temperature of this order of magnitude and greater, clearly do not agree with his. Before this discrepancy can be properly evaluated, it is necessary that the technical differences between the experiments be considered. As was mentioned previously, the basic apparatus differed in two respects: in addition there was a difference in the procedure as well as in the type of subjects employed.

First, let us consider the differences in the apparatus. It would seem that the fact that the actual symbols used were different should not have any appreciable effect on performance.

The other difference in the apparatus was that in the present experiments there were no shields attached to the moving part of the display. As was indicated above, these shields used by Pepler were attached to the moving film in such a way that they obscured the stationary cards from time to time ; this forced the subject to make some comparisons at definite times rather than leaving the timing free. There seem to be two primary effects which these shields would be expected to have. First, the subject would be required to organize his attack in order to avoid missing comparisons of particular cards because of the disappearance of the stationary card behind a shield. The second effect would be essentially that of giving the subject less time for each comparison since he would be required to spend a certain amount of his time scanning the display to see which comparison should be made next. With respect to the first of these effects, the important question is, " Was the organizing required by the shields more vulnerable to the possible effects of temperature than that required by the spacing of the moving and the stationary cards ? " Although there is no clear-cut basis for a decision, it is felt that, since the organizing is learned rather well during the training period, there would probably be no appreciable differential between the vulnerability of the two types of organizing required. The second effect, that of reducing the amount of time available for each comparison, implies that, if the shields are removed, the task is made easier. i.e. the subject is given more time for each comparison. Thus, the removal of the shields in the present experiments would be expected to make this task more nearly comparable to the slower speeds used by Pepler, i.e. the speed which permitted approximately 8 seconds per comparison in his first experiment and 6 seconds in his second.

Probably the most important difference in the two experimental designs was the fact that the subjects in the present experiment were college students, whereas the subjects in Pepler's experiment were naval enlisted men. In previous reports issued by the Medical Research Council Applied Psychology Research Unit, it has been pointed out that there is probably a difference between the way college students as opposed to the way naval enlisted men handle such experimental tasks.

The primary factor in determining successful performance on this task seems to be the ability of the subject to maintain a fairly high level of attention to detail through some sort of organized attack. The basic task itself is not very difficult as is indicated by the relatively small number of errors committed. Therefore, the results of the present experiments suggest that the subjects in the present experiments developed a plan of attack during the learning phase and were able to execute this plan with no decrement even at rather extreme temperatures.

It is felt that the group tested at 120°/105°F in Experiment II represents a special case. These subjects were starting out under this condition without any previous experience in the temperature chamber. The two subjects who were unable to complete the runs stated that they had included a fair quantity of alcoholic beverages in their diets for the previous evening. This fact in and of itself would probably be sufficient to account for their inability to complete the test. The subjects who did complete the run at this temperature showed a change only in the number of errors made. It should be pointed out that under this temperature condition, the subject tends to perspire profusely, and that this has several effects including a tendency to interfere with vision.

It is concluded that, within the range of temperatures used, there was no effect of increased temperature on the performance of this task among the subjects tested. However, the results of Experiment II for the 120°/105°F condition suggest that this may be near the upper temperature limit for performance of the task by an unprotected subject.

The present author feels that the discrepancy between Pepler's and his own experiments could be best accounted for in terms of the different types of subjects used, or in terms of the fact that Pepler's subjects performed for somewhat longer periods of time at each session.

Onze personnes ont été soumis a l'épreuve d'accomplir une tâche mentale complique pendant une hour tout en supportant quatre conditions de temperature, comme suit : ampoule soche/ampoule mouillé, 85°/75°, 90°/80°, 95°/85° et 100°/90°F. Dans la seconde épreuve dix personnes ont été epreuvées a 85°/75°, 90°/80°, 110°/90° et 120°/90°F. Dans les deux épreuves des differences d'accomplissement sous les temperatures differentes etaient petites et insignificantes.

Elf Personen wurden überprüft an einer komplizierten Geistesarbeit während der einstündigen Exponierung zu den folgenden vier Temperaturzuständen, geschafft durch Anwendung der Trocken- und Feuchtglübirnen : 85°/75°, 90°/80°, 95°/85° und 110°/90°F. Zehn Personen wurden geprüft im zweiten Versuch in den folgenden Temperaturzuständen : 85°/75°, 90°/80°, 110°/90° und 120°/90°F. Die Abweichungen der Leistungsfähigkeit waren in beiden Versuchen klein und belanglos.

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ENVIRONMENTAL CONDITIONS AND DRIVING EFFICIENCY: A REVIEW

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The paper is a review of work in the field of environmental effects on human performance with special reference to problems of driving efficiency. It is concerned principally with the effects of low and high environmental temperatures, and of air pollution by carbon monoxide, on sensori-motor performance at tasks related to driving. There are many papers and reviews dealing with the general problem of environment and occupational efficiency but relatively few concerned directly with motor vehicle driving. This is probably due to difficulties and dangers of experiments on the roads which might lead to reduction of driving efficiency and to the intrinsic difficulty of measuring driver performance. This review must be regarded therefore as a guide to the possible effects which environmental conditions may have on motor vehicle driver performance and a pointer to the need for further research more pertinent to the driving problem itself.

§ 1. Introduction

In recent years it has become standard practice to fit heating devices in private motor cars for the comfort of the driver and passengers. Some road vehicles, e.g. bicycles and motorcycles, present peculiar difficulties in this respect, although the driver, by virtue of his exposed position, may be subject to more severe body cooling than drivers of other vehicles. At the other extreme, the climatic conditions in certain countries provide an undesirably hot atmosphere for the driver and some form of air cooling system may be considered necessary.

It has been proposed by Lamburn (1957) that a heater should be capable of maintaining an average temperature of 75°F (dry-bulb) inside the vehicle with an outside air temperature of 0°F, while cooling systems should aim to reduce the temperature of the air inside the vehicle by about 10° to 15°F below ambient temperature. Adequate ventilation, he suggests, should be possible with the windows closed, so that noise can be reduced to a minimum and draughts and buffeting eliminated.

The range of tolerable levels of environmental temperature and air movement is, of course, modified by the amount and type of clothing worn and it must be remembered that in cold weather the driver of an enclosed vehicle is likely to be wearing much heavier clothing than in mid-summer. The variety of specialized clothing which the cyclist and motor-cyclist may wear is quite considerable.

However, it is not the purpose of this paper to consider the methods of protecting the vehicle driver from the vagaries of the elements but simply to review the evidence available concerning the effects of certain environmental conditions on the efficiency of the driver and his susceptibility to accidents.

Although statistics are available to show the effect of particular weather conditions on the road accident rate, it is not known whether the correlation is due solely to alterations in road surface characteristics and associated factors or if the effect may be partly due to a change in the reactions or alertness of the vehicle driver.

Osborne and Vernon (1922) made the first detailed observations of the influence of temperature on accident frequency during the first world war. They found that minor accidents (cuts) incurred by munition workers engaged on light or moderately heavy work were lowest when the environmental (dry-bulb) temperature was between 65° and 69°F, while they were 23 per cent higher at temperatures greater than 77°F and 34 per cent higher at temperatures lower than 55°F. Vernon (1940) has suggested that the higher accident rate at low temperatures was probably due to a reduction of finger dexterity, as the workers studied were frequently handling cold metal objects, and he suggested that the relatively greater number of accidents at high environmental temperatures was due to the discomfort experienced, which caused carelessness and fatigue.

More recent studies have shown a similar association between environmental temperature and accident rate in various occupations, notably in the coal mining industry. However, data of this sort are strictly limited in their application and can only indicate the need for attention to environmental conditions which can be better evaluated by properly controlled experimental investigations.

There is a considerable number of papers and reviews dealing in a general way with the effect of environmental temperatures on occupational efficiency but relatively few are concerned with the motor vehicle driver. The most relevant surveys of the field are those by McFarland and his associates (McFarland *et al.* 1954, McFarland 1955, McFarland and Stoudt 1955, McFarland *et al.* 1955). McFarland *et al.* (1955) point out (p. 87) that . . . " The variables of temperature and humidity, *per se*, have not been specifically studied as contributing causes to vehicular accidents, either in terms of a direct effect upon driver performance, or of reduced efficiency as a function of discomfort and fatigue."

From indirect evidence, McFarland *et al.* (1954) consider the following conditions of temperature, humidity and ventilation as optimal for the vehicle driver (p. 81): " For air temperature, the ideal range is 68° to 72°F, although it should be remembered that general performance does not show a rapid deterioration until 92°F. Manual dexterity, on the other hand, falls off markedly at temperatures below 50°F. Relative humidity, closely correlated with temperature in so far as comfort is concerned, is preferable when between 25 and 50 per cent. However, high humidities have little effect on comfort at temperatures below 85° to 90°F, but at humidities below 15 per cent, irritation of the eyes and of the oronasal membranes becomes pronounced. The third factor, ventilation, must be expressed in terms of the amount of fresh air supplied to the individual . . . In general, thirty-five to forty cubic feet per minute of fresh air per individual will be adequate to eliminate carbon dioxide, dispel body, tobacco and other odours, and ensure comfort ".

" Of greater importance, from the point of view of ventilation in motor vehicles, is the problem of carbon monoxide. Two to four parts per 10,000 will result in headaches after 2–3 hours exposure; at 10–12 parts per 10,000, an hour's exposure can be dangerous; and fatal at 35 parts per 10,000."

However, other investigators have recommended somewhat different values for the ideal working conditions in comparable occupations and a useful discussion of the value and limitations of these recommendations in relation to the various scales of thermal comfort employed is contained in the book by Bedford (1948). It is quite clear that people differ appreciably in what they consider to be a comfortable thermal environment. Moreover, differences between populations of different countries may also be expected, due to racial factors, habits and degree of acclimatization. It does not follow of course that the most desirable range of environmental conditions, from the point of view of comfort of the majority of people, necessarily coincides with the optimum range of conditions for efficiency of performance; it is quite possible that some degree of discomfort may be suffered without any apparent concomitant reduction in efficiency. The present paper will therefore be confined to a discussion of the experimental evidence concerning the effects of high and low environmental temperatures and of carbon monoxide on the performance of tasks which may be related to the occupational demands of the motor vehicle driver.

The absence of any direct experimental evidence of the effect of the three main environmental variables of temperature, humidity and air movement on driver performance is probably due to (*a*) the difficulty and danger of testing on the road anything which may reduce driver efficiency, and (*b*) the problem of finding an appropriate and adequate means of measuring changes in driving proficiency (Jones *et al.* 1941, Lewis 1956). The results obtained from laboratory experiments and industrial situations can only provide a guide to the possible effects which different environmental conditions may have on the motor vehicle driver in practice, and it seems worth while to consider in some detail the sorts of tasks on which changes in performance have been detected. The effects of humidity and air movement will be considered where appropriate in relation to different environmental temperatures. The effects of local and general body cooling will be discussed first.

§ 2. Effects of Low Environmental Temperature

Heat loss from the body is primarily dependent on the temperature difference between the body and the surrounding air and on the rate of air movement over the body surface, and these factors have been used to compile a wind-chill index to indicate the cooling power of the environment (Siple and Passel 1945). Although the wind-chill index may be appreciably modified by the amount and type of clothing worn, there are adequate reasons for believing that it holds fairly well in practice (van Dilla *et al.* 1949, Burton and Edholm 1955, p. 112) for the unprotected or relatively little protected parts of the body, such as the hands and face.

This is much more relevant to motor cyclists and cyclists than to drivers of enclosed vehicles. Even a slight air movement appreciably increases the cooling power of a particular air temperature, and the effective air movement over the hands of a motor cyclist may be considerable. One of the results of such cooling is to reduce the strength of opposition of the thumb and fingers so that the operation of certain mechanisms (such as the clutch or hand brake) requiring this type of movement may be considerably impaired, and the simple reaction time to a stimulus may be significantly prolonged (Craik and Macpherson 1943, Teichner 1958). According to Russell (1957) the optimum range of air temperatures (with no air movement) for maximum hand grip strength is from about +50°F to +86°F (dry-bulb), while other studies suggest that the maximum length of time for which a particular grip may be applied also varies with environmental temperature (Clarke *et al.* 1958).

Many other studies have been made of the effects of low ambient temperature on the efficiency with which various manual tasks may be carried out, and all show some deterioration of performance with exposure to cold. In the recent report by Russell (1957) there is a useful summary of much of the available evidence on the subject, but the interpretation and application of the results of many of these experimental studies is fraught with difficulties. It was shown long ago by Perrin (1921) and Muscio (1922) that there is very little correlation between performance on one test of motor ability and another, no doubt because there are usually so many uncontrolled variables present. For example, until recently relatively few investigations of manual skill included any attempt to control what muscles or joints are used in the tasks studied, while the dependence of motor performance on sensory information from the limbs is still very imperfectly understood (Provins 1957).

The demonstrated reduction of tactile discrimination and other forms of kinaesthetic sensitivity with a lowered environmental temperature (Mackworth 1953, Mills 1956, Russell 1957) may directly affect driver efficiency by reducing his 'feel' of the vehicle. Such information about the responsiveness of the steering may be particularly important when driving over icy roads, and especially at night or in other conditions of reduced visibility. Some aspects of kinaesthetic sensitivity appear to be impaired at air temperatures below about 50°F (Russell 1957), and this limiting temperature is likely to be somewhat higher if there is very much air movement. Wet–cold conditions may also raise this temperature value to some extent.

There is relatively little evidence available concerning more general effects of cold on performance of tasks related to driving efficiency. Recent studies by Teichner and Wehrkamp (1954) and Teichner and Kobrick (1955), however, have shown that tracking performance is definitely impaired by both short ($\frac{1}{2}$ hour) and prolonged (12 days) exposure to an environmental temperature of 55°F. Chronic exposure to cold with consequent cooling of the face and extremities can produce severe pain (Wolf and Hardy 1943, Horvath and Freedman 1947, Blaisdell 1951) which may be a source of considerable distraction, although it has been suggested that less extreme cold may actually increase alertness rather than depress it (Barmack 1939). Unfortunately, there appears to be no direct evidence on this point, but from theoretical considerations (Broadbent 1953) an optimal range of air temperatures for vigilance would be expected, dependent to some extent on the duration of the exposure and the level of other environmental stimuli present, such as noise or vibration. Certainly there is evidence of an impairment of vigilance at high environmental temperatures and this is discussed in the following section.

§ 3. EFFECTS OF HIGH ENVIRONMENTAL TEMPERATURE

In contradistinction to investigations of low environmental temperatures, studies of the effects of heat on human performance have been concerned mainly with general impairment of efficiency rather than with any local effects on manual dexterity.

However, of the little evidence which is available concerning such factors as muscular strength, tactile discrimination and manipulative ability, the most relevant studies are those of Weiner and Hutchinson (1945), Carpenter (1950), Mackworth (1950), Pepler (1956), Russell (1957) and Clarke *et al.* (1958).

The effect on muscular strength was studied by Clarke *et al.* (1958) who immersed the hand and forearm in water at temperatures in the range 36°–108°F and found hand grip strength to be maximum at a temperature of 64°F or higher (within the range tested). They also measured the length of time for which a particular grip strength could be maintained and found that this was greatest at a water bath temperature of 64°F but dropped off at temperatures both above and below this value. These results are somewhat difficult to interpret in terms of air temperatures due to the vast difference in thermal conductivity of air and water. Furthermore, the somewhat contradictory evidence by Russell (1957), that at air temperatures above about 73°F (effective temperature) some impairment of maximum grip strength may be expected, suggests that further work in this field is desirable.

Among the few investigations of manual dexterity in the heat are those of Weiner and Hutchinson (1945) who showed that appreciable impairment of performance may be expected (in unacclimatized persons) after a two-hour (resting) exposure to an environment of 95°/90°F (dry/wet bulb). They suggested that the decrement in performance was due to slowed and inaccurate movements. Similarly, Viteles and Smith (1946) showed a significant deterioration of performance in several different tasks when subjects were exposed to an effective temperature (E.T.) of 87°F or higher as compared with 73°F (E.T.), although the effect was greater on some tasks than others. The more recent study by Russell (1957) has also shown a somewhat varied effect on different tasks with an increase in environmental temperature up to 86°F (E.T.). These tasks included two measures of tracking ability, one which showed a decrement in performance with increased temperature and one which did not.

The earlier investigations of the effect of high environmental temperature on tracking ability by Mackworth (1950) and Carpenter (1950) both showed some impairment of performance in acclimatized subjects at temperatures of about 87°F (E.T.) as compared with an effective temperature of 79°F, while Pepler (1956) has shown a similar drop in efficiency on the same type of task at 91°F (E.T.) as compared with 65°F (E.T.). Pepler points out that the reason for the impairment is not at all clear and that further study is required to determine the location of the heat sensitive structures responsible.

Several studies concerned with the effects of heat and high humidity on more purely mental tasks have also been reported, notably by Mackworth (1946, 1950), Carpenter (1946) and Pepler (1953 a). The study by Mackworth (1946) showed that the performance of highly trained and experienced wireless telegraphists was definitely poorer at high environmental temperatures and that the critical level was 90°F (E.T.). The operators who took part in this investigation were artificially acclimatized to heat by short daily exposures in a hot chamber. During the three hour test period a gradual decrease in efficiency was recorded, more marked at the higher temperatures and least apparent in the best operators. These findings were generally confirmed by Pepler (1953 a) in a similar study carried out in Singapore on a group of well-qualified telegraphists who had been serving in the tropics for at least six months prior to testing.

The investigation by Carpenter (1946), using a task which correlated well with an established intelligence test, also showed that performance decreases with increase in environmental temperature and that the deterioration becomes statistically significant at an effective temperature of about 90°F. Similarly, on the problem-solving test employed by Mackworth (1950) subjects showed an appreciable drop in efficiency at the higher environmental temperatures used, with the critical level again at about 90°F (E.T.). In both studies, the experimental subjects were artificially acclimatized to a hot environment by short daily exposures for two to three weeks prior to testing.

Of considerable importance to vehicle driving is the concept of vigilance put forward by Mackworth (1948) and later elaborated in his more extensive monograph (Mackworth 1950). The effect of atmospheric temperatures of 70°F, 79°F, 87·5°F and 97°F (E.T.) on vigilance or alertness was studied by Mackworth (1950) on artificially acclimatized men during a two-hour watch period. He found that performance was not only poorer at the higher environmental temperatures tested but that there was a more marked deterioration of efficiency within the two hour spell, with optimum conditions at 79°F (E.T.). The general conclusions from Mackworth's study were later confirmed by Pepler (1953 b) on naturally acclimatized subjects in Singapore.

The investigation by Bursill (1958) on heat acclimatized subjects primarily engaged on a tracking task, but who were also required to respond to occasional signals in the peripheral visual field, provides a situation more closely comparable with that of the motor vehicle driver. Bursill exposed men to temperatures of 70°/60°F or 105°/95°F (dry/wet bulb) and an air movement of 120 ft/min for either one or two hours, followed by a one-hour testing. He found that not only did the overall visual vigilance suffer more markedly at the higher environmental temperatures, but that there was a 'funnelling' of attention towards the centre of the field of view i.e. the signals nearest the periphery tended to be missed more than those located centrally.

Other studies by Fraser (1957) and Loeb and Jeantheau (1958) confirm that under conditions of high environmental temperature there is a deterioration of visual vigilance, which may be more markedly affected if the heat is accompanied by noise, vibration or hard physical work.

Most of these investigations have been conducted on heat acclimatized persons. For unacclimatized persons the temperature at which a significant deterioration takes place may be somewhat lower, although further information on this point is obviously desirable. Furthermore, most of the studies have employed conditions in which the degree of air movement has been adjusted to about 100 ft/min. It is rather difficult to say what the minimum air movement in a motor car or driving cab may be in practice, but preliminary measurements at face level using an ion anemometer in a 1955 private car with the windows fully closed gave a steady value of about 33 ft/min irrespective of road speed (Provins and Hellon, unpublished observations). The amount of air movement preferred or tolerated without discomfort increases with the environmental temperature (McFarland 1946, p. 112–114). In the absence of any form of air conditioning system the driver would presumably open a window to improve the air movement in hot weather, while draughts due to incomplete sealing of doors and windows may also be anticipated in commercial vehicles and older cars.

§ 4. Effect of Air Pollution

Apart from considerations of the amount of air movement, there is also the question of whether fresh air should be used in the air conditioning of enclosed vehicles, or whether relatively stale air should be recirculated. It is, of course, difficult to assess how stale the air in a particular vehicle may become, as this is so obviously dependent on such factors as the number of occupants and adequacy of the sealing of doors and windows. According to Hill (1920) a rise in CO_2 concentration to between 1 and 2 per cent causes no discomfort or measurable impairment of efficiency and cannot be detected by the occupants of a room even if suddenly increased to this value, although the recommended maximum concentration in which a person may work for eight hours daily without adverse effect is 0·5 per cent (American Conference of Governmental Industrial Hygienists, 1957). More important, perhaps, is the concentration of potentially toxic gases in the atmosphere surrounding the vehicle driver. Of these, carbon monoxide is probably the most important, and is primarily derived from two sources: (*a*) tobacco smoke and (*b*) vehicle exhausts. The concentration of carbon monoxide in tobacco smoke may be between about 1 and 8 per cent by volume (Armstrong 1922) although the concentration in the air inside a vehicle is again dependent on the sealing of windows and doors and the number of people smoking. It is of some interest however, that Hanson and Hastings (1933) tested the carbon monoxide saturation of the blood in seven smokers and found 3–4 per cent compared with about 1·5 per cent for seven non-smokers, while Barach, Eckman and Molomut (1941) reported that in " 18 inhaling smokers, the average CO saturation of arterial blood was 5·7 per cent after smoking 20 cigarettes from 9 a.m. to 4 p.m. Nine of the subjects had a carbon monoxide saturation between 5 per cent and 10 per cent ". Unfortunately, these last-named authors do not give the CO saturation of the blood of their subjects before smoking nor a comparable analysis for a control group of non-smokers over the same period. However, McFarland (1946) has shown that "Deep inhalation of the smoke from a single cigarette caused an increase of almost 2 per cent in the saturation of the blood with carbon monoxide. After inhaling the smoke of three cigarettes, the carboxyhaemoglobin in the blood rose, on the average, 4 per cent ". Presumably the effects of tobacco smoke would be minimized by a constant supply of fresh air to the driver, although according to McFarland (1946) the elimination of carbon monoxide from the blood is very slow.

On the other hand, air drawn from outside the vehicle may add to the carbon monoxide content of the air breathed. The exhaust gases from motor vehicles may contain, for example, up to as much as 13·5 per cent of carbon monoxide (Fitton 1956) although the concentrations which have been recorded in the general atmosphere at face level in various European and American towns are mostly below 0·01 per cent but occasionally higher (Wilkins 1956). In a recent series of investigations at particular sites in London, Lawther (personal communication) recorded values in excess of 0·03 per cent at chest height on the pavement, so that the concentration between vehicles in a line of traffic may be somewhat greater than this. As exposure to concentrations of 0·06 per cent or higher for an hour can produce headaches and nausea, it seems possible that some traffic conditions would constitute a definite hazard. From this it follows that the positioning of the air intake for the heating or cooling device is particularly important. It should be placed so that there is no likelihood of it ever being in close proximity to the exhaust from other vehicles, for breathing such an atmosphere, a man may be rendered helpless in a matter of minutes without realizing that he is affected (Hunter 1955, p. 570).

Unfortunately there seems to be little evidence available to suggest at what level a deterioration in sensori-motor performance may be expected. A very useful review of the effects of carbon monoxide on human performance in relation to problems of flying and aircraft design may be found in the book by McFarland (1946). An investigation by Forbes *et al.* (1937), on the effects of breathing pure carbon monoxide at a concentration of 0·09 per cent and vehicle exhaust gases at a slightly higher concentration, showed no decrease in performance of eight subjects on a number of tests, although after an hour two subjects had a concentration of CO in the blood of about 50 per cent and were on the point of collapse. The tests used were measures of: (*a*) brake reaction time, (*b*) perception of depth, (*c*) ability to see dim objects beside a bright light, (*d*) ability to perceive the approach or recession of objects, and (*e*) tracking accuracy. The authors state that both of the two subjects who were most affected "were well aware that they were unable to drive a car and were not far from collapse, but they were able to concentrate on a test long enough to do it reasonably well" (p. 602).

A more recent and successful investigation by McFarland, Roughton *et al.* (1944), using an extremely sensitive test of visual efficiency, has shown that the visual threshold to a stimulus at a low level of general illumination increases as the concentration of carbon monoxide in the blood increases. In fact, the effect is indistinguishable from the effects of anoxia, which, from what is understood of the mode of action of carbon monoxide in the blood, is not very surprising. Further experimental work is desirable to confirm these findings on a broader basis. In the meantime it is reasonable to predict the safe limits of exposure to carbon monoxide from the degree of anoxia produced.

The maximum average atmospheric concentration of carbon monoxide for a daily exposure of eight hours without injury to health has been set at 0·01 per cent by the American Conference of Governmental Industrial Hygienists (1957). This coincides closely with the recommended value of 12 per cent quoted by McFarland (1946, pp. 240–1) for the maximum permissible carboxyhaemoglobin concentration in the blood of aircraft crews engaged on long flights under non-combat conditions, agreed by the U.S. Army, Navy and civilian authorities.

It seems unlikely that the concentration of carbon monoxide in the blood from either tobacco smoke or the atmosphere of busy streets will, by themselves, cause a significant impairment of efficiency in the vehicle driver under otherwise normal circumstances. On the other hand, it is possible that, in combination and under extreme conditions, an undesirable level of carbon monoxide can accumulate in the blood of healthy individuals. In persons suffering from certain ailments, and particularly anaemia, the consequences would probably be more serious or more easily provoked. It is outside the scope of this review to consider the possibility of engine fumes reaching the inside of the vehicle due to a leaky exhaust system or some other fault of maintenance or design. But the likelihood of pollution of the air inside the vehicle by carbon monoxide and other toxic gases from this source must not be underestimated, particularly in older vehicles. However, according to McFarland (1946) "The constituents of engine-exhaust gas other than carbon monoxide are either so much less toxic than carbon monoxide or are present in such small quantities that they are of little practical importance. Contamination of the cabin air with exhaust gases results in serious degrees of carbon monoxide poisoning before any other constituent can produce toxic effects". Although this statement was made with reference to aircraft engines and is no doubt also applicable to the exhaust gases from petrol engines of road vehicles, there is evidence that the effects of diesel fumes need to be considered separately, due to the relatively low carbon monoxide content of the exhaust gases; typically, about 0·1 per cent for the diesel engine and about 4 per cent for the petrol engine (Fitton 1956). An investigation by Pattle *et al.* (1957) has shown that the toxicity of the constituents of diesel exhaust fumes and their relative importance vary appreciably according to the working conditions of the engine. However, they conclude that there is "No reason to suppose that the toxicity of the fumes from the petrol engine, even if it were not masked by their much greater carbon monoxide content, would be less than that of diesel fumes; they might however have less effect on the trachea and bronchi than do diesel fumes. The main objection to diesel fumes seems to be their irritant nature" p. (54). In this respect they found that, under certain operating conditions, exposure of the observer's eyes to the fumes for only a few seconds caused intense and lasting pain and lachrymation. When a 'good' fuel injector in the engine was replaced with a 'worn' one, the exhaust fumes were appreciably less irritant. This, they suggest, indicates that the requirements for mechanical perfection in an engine are not necessarily identical with those for a physiologically harmless exhaust. The exact nature of the irritants is not yet known, but it seems possible that even in considerably reduced concentrations they might have effects likely to cause some discomfort and distraction to a vehicle driver, with perhaps blurred vision due to excessive lachrymation.

On passe ici en revue le travail dans le domaine de l'action du milieu sur le rendement humain, ayant égard particulièrement aux problèmes de la compétance à conduire. On s'occupe surtout de l'action des températures basses et elevées du milieu, et de l'action de la pollution de l'air, surtout par l'oxyde de carbone. Il y a beaucoup d'études et de revues où on s'est occupé du problème générale du milieu et du fonctionnement dans le travail, mais il n'y en a relativement pas beaucoup sur le problème de la conduite des voitures. Cela est probablement dû aux difficultés et aux dangers qu'il y a à faire sur les routes des expériences qui pourraient mener à une réduction dans la compétence à conduire, et à la difficulté intrinséque de calculer de la compétence dans la conduite d'une voiture. Cette revue doit donc etre considerée comme une indication des effets possibles qu'exercent les conditions de milieu sur la compétence des conducteurs de voiture et comme démontrant le besoin de recherches plus pertinentes au problème de la conduite lui-même.

Diese Veröffentlichung gibt einen Ueberblick über Arbeiten auf dem Gebiete der Wirkung der Umgebung auf die menschliche Leistung unter besonderer Berücksichtigung der Güte der Leistung von Kraftfahrern. Sie befasst sich hauptsächlich mit den Wirkungen niedriger und hoher Umgebungstemperaturen und mit den Wirkungen von Luft-Verunreinigung vorweigend durch Kohlenoxyd. Es gibt viele Veröffentlichungen und zusammenfassende Darstellungen über das allgemeine Problem der Umgebungs-Einflüsse auf die Leistungsgüte, wenige aber, die sich unmittelbar mit dem Fahren eines Motor-Fahrzeuges befassen. Das mag durch die Schwierigkeiten und Gefahren von Experimenten auf der Strasse bedingt sein, die zu einer Minderung der Leistungsgüte und zu einer grundsätzlichen Schwierigkeit der Messung der Leistung des Kraftfahrers führen können. Dieser Ueberblick kann daher nur als Einführung in die wahrscheinlichen Wirkungen dienen, die der Kraftfahrer durch die Umgebung erleidet. Sie soll zugleich auf die Notwendigkeit weiterer Forschung hinweisen, die dem eigentlichen Problem des Kraftfahrers noch besser angepasst ist.

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LETTERS TO THE EDITOR

Dear Sir,

Mr. Fosberry's article in the May 1958 issue (Vol. I, pp. 240–250) is most appropriate as a statement of one method used in determining driver visibility. There are, however, a number of points that bear comment.

There is, as suggested, a significant advantage to be gained from determining the undeflected seat point from a fixed reference such as the mid-point of the accelerator pedal. However, the use of single values for seat–accelerator and seat–eye point distances in determining visibility tends to overlook anthropometric variability. It seems more meaningful to sample a range of values limited by the 10th and 90th percentile dimension of the driving population when determining these distances. This procedure results in an ellipsoid within which the population eye points will fall. It would then be appropriate to use the limits of this ellipsoid in determining the extent of visibility. It is believed that the $26\frac{1}{2}$ in. eye point dimension has value for specific styling considerations but leaves something to be desired as a research dimension.

In addition, I might suggest that there would be greater utility of visibility data if they were presented in relative terms. For example, a comparison could be effected between the ideal unobstructed view (as might be seen by a person seated in a chair on a roadway) and the visibility remaining as a result of enclosure in a vehicle. It is felt that such a comparison between the ideal and the actual, with regard to critical visual areas might achieve greater comparability of visibility limits among many types of vehicle.

Research Staff,
General Motors Corporation,
Box 188, North End Station,
Detroit 2, Michigan.

Yours faithfully,
David B. Learner, Ph.D.,
Senior Research Psychologist.

Dear Sir,

The point raised by Dr. Learner concerning the limitations of a single value setting of the eye position is one of which we are conscious. The use of a single setting is, however, at the moment justified by the necessity to gain acceptance of the method. A single setting has the advantage of simplicity, and refinements of the type suggested by Dr. Learner could be included at a later stage. It may be noted, however, that some important information on the effect of movements of the eye position can in fact be derived from the present method; thus if the eye to windscreen pillar distances are known the effect of vertical movements on pillar obscuration can be predicted. A further modification, which could be included, would be the use of a dummy or weight to allow for variations of seat softness and angle.

Concerning the presentation of visibility data in relative terms, the forward visibility ground plan does this in a sense, by showing the ground areas obscured by the vehicle body components. To compare these areas in relation to an actual traffic scene might make visual interpretation easier, but the particular scene chosen would tend to bias the interpretation. Scenes could also be superimposed on the forward screen diagrams and this effect was obtained in the pre-war *Autocar* road tests, which presented drawings taken from the cars when parked in a particular spot in a street.

The Motor Industry Research Association,
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Warwickshire.

Yours faithfully,
R. A. C. FOSBERRY.

SUMMARIES OF PAPERS PUBLISHED ELSEWHERE

Authors of papers of ergonomic interest which have been published in other journals or which are available as privately circulated reports are invited to submit summaries for publication in this Journal. They may be sent to any member of the Editorial Board and should be accompanied by a copy of the full paper which will be returned to the author on request.

Welford, A. T. (1958), Some preliminary thoughts on the human demands of automation. *Brit. J. industr. Med.*, **15**, 99–104.

An attempt is made to outline some of the factors in human skilled performance which seem, from the standpoint of experimental psychology, likely to be of importance in work with automation equipment.

Automation appears to reduce the need among operators for actual manipulative skill but to place increased emphasis upon a number of more intellectual capacities. These demands are discussed in terms of (1) the limited 'information channel capacity' of the human organism with the suggestion that both over- and underloading of this capacity are to be avoided; (2) the need for consistency in the relationships between display and control; and (3) the coordination of data from many sources and arriving at different times, and the conceptualization of the task which appears to be necessary for adequate performance.

Briefer discussion is included of the problem of what constitutes adequate information in displays, of the most suitable routines for repair work, of the urgent need to devise methods of re-training middle-aged operatives who have to be redeployed, of what is meant by 'responsibility' on the part of operatives, and of the likelihood that automation will result in gains as well as losses in work satisfaction.

Harper, R., McKennel, A. C. and Onions, W. J. (1958), The subjective assessment of quality in wool tops. *J. Text. Inst.*, **49**, 126–140.

The traditional wool quality scale provides an opportunity to study various aspects of the use and development of mental reference standards. Amongst the aspects considered here are: the sensory basis of judgment, the effects of training, and subjective objective relationships. The task of matching an unknown sample with one of a set of reference standards can be carried out equally well by sight alone as by the free use of all the relevant senses. In commercial practice the actual matching technique is rarely required, for the quality number of a sample of wool tops will be recognized with little difficulty by the trained assessor. In a series of experimental tests over a period of about twelve weeks, judgment either with or without an immediately present reference standard showed a progressive improvement with time to a level which compared well with that of established experts. Individual differences were noted in the consistency of judgment from one occasion to another and in some other matters. One or two persons were equally good at both types of judgment. An independent study of visual discrimination between pairs of individual fibres yields a value of 2–3 microns as the difference which is likely to be detected with a 75% chance of success. Although it is most unlikely that discrimination between samples of wool tops, which consist of combed fibres in bulk form, is carried out on the basis of individual fibre assessment, pairs of wool tops discriminated from one another with the same degree of success (75%) also show a difference in average fibre diameter, measured instrumentally, of about 2 microns. A further comparison of subjective assessment with the maker's original specification on the samples and measurement data reveal inconsistencies which have important practical and theoretical implications.

See also McKennel, A. C. (1958), Wool quality assessment :

A. Its sensory and psychological basis. *Occup. Psychol.*, **32,** 50–60. (Abstract: *Ergonomics*, **1,** 289) ;

B. The acquisition of skill. *Occup. Psychol.*, **32,** 111–119,

for a slightly more expanded treatment of these two aspects of the work reviewed above.

Fleishman, E. A. (1958), An analysis of positioning movements and static reactions. *J. exper. Psychol.*, **55,** 13–24.

Fleishman, E. A. (1958), Dimensional analysis of movement reactions. *J. exper. Psychol.*, **55,** 438–453.

These two studies concern three types of task in which the subject was required (*a*) to hold his hand or limb in a steady position, e.g. by holding a stylus in a fixed position (static reactions); (*b*) to make accurate movements such as reproducing the extent of movement of a stick control, and moving a knob to an estimated position along a slot (positional movements); and (*c*) in which the ability to make smooth or coordinated movements is of more importance than accuracy (movement reactions), e.g. various forms of compensatory and pursuit tracking, and certain simple and discriminatory tasks Factor analysis was employed in the examination of the results of 200 and 204 subjects who performed on the first and second battery, respectively. The conclusions may be summarized as follows. (*a*) *Static Reactions.* These can usefully be regarded as a separate class of skills from positioning movements. They bear a strong common feature, identified as Arm–Hand Steadiness. (*b*) *Positioning Movements.* A high degree of specificity is associated with each of the several tasks in this category. Subjects performed very consistently on individual tasks, but little prediction could be made from performance on one to performance on another. Such similarities in performance as did exist suggested that tasks involving the reproduction of a specified movement or limb position are of a different class from those requiring the estimation of a limb position not previously experienced. (*c*) *Movement Reactions.* Tasks of this type may be grouped into several categories, each requiring a common ability. The types of ability inferred were entitled Fine Control Sensitivity, Multiple Limb Coordination, and Response Orientation. A factor called Rate Control was considered more tentative. Other factors were identified, but these did not contribute to performance in the more complex movements under examination.

Briggs, G. E., Fitts, P. M. and Bahrick, H. P. (1958), Transfer effects from a single to a double integral tracking system. *J. exper. Psychol.*, **55,** 135–142.

The object of this study was to determine whether prior practice at a two-dimensional compensatory tracking task involving a velocity control system, affected subsequent performance at a more complex task of the same variety in which an acceleration control system was used. The simpler task involved tracking through a single stage of integration in one axis of the task, whilst the subsequent task involved tracking through a double integration.

Prior practice at the simpler task improved initial performance at the more complex one; the amount of improvement increased with the amount of prior practice. Increases in amount of prior practice with the velocity control system reduced the amount of subsequent practice needed in the more complex task for a criterial level of performance to be reached.

In order to avoid delay in the publication of papers, the present number of the Journal is considerably larger than normal. The size of the next three numbers will be adjusted to provide a Volume having a total of about 400 pages.

OBITUARY NOTICE

Craig L. Taylor

It is with much regret that we record the death of Dr. Craig L. Taylor as the result of an accident in April, 1958 at Los Angeles, California.

Craig Lee Taylor was born at Edmonds, Washington on 3rd May, 1909. He was educated at Washington (Seattle), where he obtained the B.S. degree in 1933, and at Stanford, where he gained his M.A. in 1939 followed by the Ph.D. degree in physiology in 1940.

From 1939 to 1943 he was a member of the department of physiology at Stanford, first as instructor and subsequently as assistant professor of hygiene and physiology. During the war he was engaged on research studies in aviation physiology as a member of the United States Air Forces. From 1946 to 1950 he held the appointment of associate professor of engineering at the University of California, Los Angeles, and in 1950 was promoted to the chair of biomechanics, the appointment he held at his untimely death.

Taylor was interested in the application of physiological knowledge to the study of technical problems involving human performance. His special fields of interest were the physiology of exercise and of high temperature. His studies of the effects of high radiant temperatures are well known. They were conducted with an enthusiasm that must have been difficult to maintain in face of the technical difficulties of the subject.

Craig Taylor was a member of the Ergonomics Research Society and attended the symposium held at Ashorne Hill in 1954. It will be of interest to members of the Society to note that his career must have been unique in that he was probably the first physiologist ever to have been appointed to a chair of engineering.

EDITORIAL NOTE

Since the time this Journal started Dr. W. F. Floyd has done the work of seeing anatomical and physiological papers through the various stages of editing. The Editors, the Council of the Society and the Publishers are glad that he has agreed to his contribution being recognized by consenting to be named as Associate Editor (Anatomy and Physiology).

They are also pleased to announce that Dr. R. B. Bromiley, Chief of the Applied Experimental Psychology Section of the Defense Medical Research Laboratories, Toronto, Ontario, Canada has joined the Editorial Board.

ERGONOMICS RESEARCH SOCIETY

PROCEEDINGS

A Meeting was held jointly with the British Occupational Hygiene Society at the London School of Hygiene and Tropical Medicine on 27th June, 1958.

The following were elected as Ordinary Members :—

Mr. D. W. S. Alloway
Mr. J. Annett
Dr. M. A. Bouman
Mr. R. T. Eckenrode
Surgeon-Commander W. H. B. Ellis, A.F.C., M.D.
Mr. S. D. M. King
Mr. A. R. Lind
Dr. R. D. Pepler

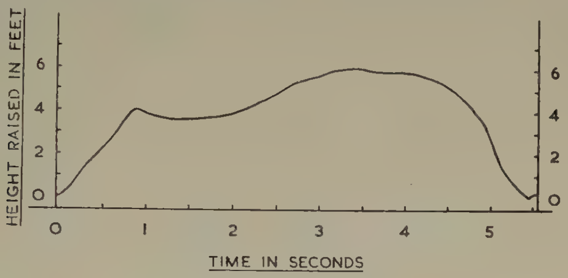
The following papers and demonstrations were presented :—

(1) " Photographic Methods for Estimating External Lifting Work in Man ", by J. G. Fletcher and H. E. Lewis, Division of Human Physiology, Medical Research Council, and D. R. Wilkie, University College, London.

It is possible to use photography to measure external lifting work of a few seconds' duration, provided the movement takes place in one plane. Two methods have been used in a preliminary study of the power output (h.p. or kgm/min) of athletes lifting barbell weights, (*a*) slow motion cine-photography and, (*b*) still photography with a revolving camera.

In the first method the lateral movements of the barbell are filmed. In the same photographic plane, a height scale is provided, which consists of a vertical column with small lights placed at 1 ft intervals ; a time marker, consisting of a light flashing precisely every ½ second is placed in view ; and for convenience of pinpointing the centre of the barbell on the film, a small light is attached to the axle in the same plane as the height and time scales.

Accurate timing is necessary because slight variations occur in the speed of film through the cine-camera. For analysis, the processed film is projected frame by frame on a white card and the positions of the barbell light are marked on it in sequence. The marks appear close together wherever movement is slow and more widely spaced when movement is rapid. The interval separating every mark represents 1/64 second. Measurements are made of the vertical height of each point above the resting position and are plotted against the elapsed time on a graph as in the figure.



In the second method, the illuminated barbell, the vertical column of lights and the time marker, all in the same plane, are retained ; but the cine-camera is replaced by a still camera mounted on a revolving stand.

There should be a minimum of adventitious light in front of the lens. With the shutter open, the camera begins to revolve immediately before the lifting movement takes place and continues slowly throughout at a constant angular velocity. The shutter is closed when the lift is complete and the exposed plate or film is developed in the usual way. It will then be found that the vertical column of lights has traced a grid of equidistant horizontal straight lines, the time marker producing a row of dots representing $\frac{1}{2}$ sec intervals, and the moving barbell light superimposing a pattern of its vertical displacement from the resting position in the same way as a graph. In fact, the result is indistinguishable from that of the graph plotted in the figure.

If a flash bulb is discharged while the camera shutter is open it will photograph the image of the athlete at that particular moment, thus providing additional identity without obscuring the patterns traced by the small lights.

Calculations of the external work produced during that phase of lifting which corresponds to the first near linear rise, show that excellent agreement holds between the two methods. However, errors will occur in the revolving camera method if the lifting movement is not substantially a vertical one.

It was found that a well-trained professional weight-lifter, 45 years old, was capable of producing as much as 2 h.p. (9000 kgm/min) for a period of 0·6 sec while lifting 275 lb from ground level to chest height.

(2) " Demonstration of Weight-lifting ", by A. Murray, Champion Weight-lifter.

(3) " Physiological Factors concerned with Weight-lifting ", by W. F. Floyd, Department of Physiology, Middlesex Hospital Medical School, London.

The energy cost of weight lifting is relatively small in absolute value for each lifting operation carried out, although the rate of expenditure, over a short period of time, may be extremely high when judged by the standards of maintained exercise. For example, work on a bicycle ergometer at a rate of 900 kgm/min (approximately equivalent to an O_2 uptake of 2·0 l/min—50% of the aerobic capacity—and an energy expenditure of 10 kcal/min) can be maintained for long periods of time by physically fit subjects. Work at ten times this rate, incurring the maximum O_2 debt, can only be carried out in bursts for very short periods of time. Such high rates of energy expenditure are possible in the light of physiological studies of athletic performance.

Recent studies of the mechanical properties of muscle suggest that muscles are able to develop their maximal tension at about their natural, *in situ* length. Muscle consists essentially of a contractile element (C) which is functionally in series with an elastic element (E). When the muscle becomes active the C element is activated practically instantaneously and passive stretching of the E element occurs. Some of the energy of contraction is thus used up in stretching part of the muscle itself.

When shortening of a muscle occurs during activity, the velocity of shortening of the C component is inversely related to the force exerted. Thus heavy weights, requiring large forces, can only be moved slowly, thereby limiting the maximum rate at which muscle work can be done. The complete description of the mechanical performance of muscle is determined by Hill's equation extended to include the behaviour of the E component. These studies have not yet been applied, however, to the action of human muscles in practical weight lifting problems.

It is important to appreciate that the ordinary equations of motion can be used in the description of the movements of both the weight lifted and the parts of the body involved in the lifting action. Some simplifying assumptions are required, however, in order to make practical use of these equations.

Other physiological factors involved in weight lifting, about which comparatively little is known, are the questions of blood flow to the muscles and the part played by proprioceptive mechanisms in the coordination of lifting movements. Little is known also about the physiology of training for weight lifting.

Much has been written about body mechanics and weight lifting, especially in regard to the dangers of ligamentous injury to the back. It is generally believed that prolapsed intervertebral disc injury can occur most easily when lifting is carried out with the trunk flexed (the ' derrick ' method) and is least likely to occur when the trunk is extended as with the " knees bent " method of lifting.

Electromyographic studies have shown that the erectores spinae muscles, the main extensors of the back, are usually relaxed in the early stages of lifting with trunk fully flexed (' derrick ' method) and vigorously active throughout lifting with trunk extended (' knees bent ' method). Mechanical considerations make it reasonable to suppose that the intervertebral ligaments (discs) play a dominant role in the stability of the fully flexed vertebral column; in lifting from this position these ligaments are under very considerable tension. A sudden, increased strain resulting from lifting in this position may thus easily lead to rupture of a disc. With the ' knees bent ' method of lifting the strain of the load is shared by the erectores spinae muscles with consequent reduction of the load borne by the intervertebral discs.

Other electromyographic studies have shown that some people lift and carry heavy weights, up to some 30 or 40 lb, with little or no shoulder girdle muscle activity—thus imposing a considerable strain on the ligaments of the shoulder joint and passively stretching the muscles and nerves of the shoulder girdle. This may account for a proportion of the shoulder girdle injuries associated with weight lifting, such as tearing of the brachial plexus. By training, people can be taught to use the shoulder girdle muscles in lifting and so reduce the risk of such injuries.

(4) " The Working Capacity of Muscles during Reactive Hyperaemia ", by E. A. Collier and C. J. Percival, Sherrington School of Physiology, St. Thomas's Hospital, London.

During the reactive hyperaemia consequent upon a 5-minute occlusion of the forearm blood flow the working capacity of the forearm muscles was examined to establish whether any increase in working performance was apparent. Nine healthy male medical students between the ages of 19 and 28 were used as subjects.

The subject, seated comfortably with the dorsum of his forearm resting on a table in front of him, compressed a hand-held dynamometer. The dynamometer consisted of twin metal bars separated by compression coil springs ; an electrical circuit was incorporated to display a light on attaining a standard pressure. Work was performed at a rate of 90 movements/minute until exhaustion. Exhaustion was defined as the failure to achieve the standard pressure on five successive occasions. Since previous experience had shown that allowing the subjects to judge their own end point introduced psychological effects they were told to continue, regardless of other factors, until instructed to stop.

The subjects were divided into two groups A and B. Each subject performed two experiments. On the first occasion group A worked as described above, and group B followed the same procedure immediately following release of a 5-minute occlusion at 200 mm.Hg. pressure. Instantaneous application and release of pressure was achieved by the use of cuffs connected to a large pressure reservoir by a three-way tap. On the second occasion, a week later, the two groups carried out the alternative procedures. In this manner the effects of fatigue and training were eliminated. The subjects were unaware of the reason for and the results of the experiment.

During the control experiments the average duration of work was 1 min. 26 secs ; following occlusion this became 1 min 29 secs, a 3·5% increase. However, since individuals showed variations of 30 secs in either direction, it was not felt that this increase was significant. It was therefore concluded that the working capacity of these muscles was not increased during reactive hyperaemia.

These results differ from those of Nukada (1955) who described a three- to four-fold increase in working capacity during reactive hyperaemia of the calf muscles following occlusion.

(5) FILM : " Lifting and carrying stretchers ", by the Department of Applied Physiology, London School of Hygiene and Tropical Medicine,

(6) "The Duration of 'Static' (sustained) Contractions at Different Muscle Temperatures", by A. R. Lind, R. S. J. Clarke and R. F. Hellon, Medical Research Council Unit for Research on Climate and Working Efficiency Department of Human Anatomy, Oxford.

The durations of sub-maximal sustained flexor contractions of the forearm were measured on a hand-grip, strain-gauge dynamometer after the muscle temperature had been altered by immersing the forearm in water at different temperatures, from 2–42°c. Contractions were longest in water at 18°c, when the "reference muscle temperature", measured by thermocouples placed half-way between the skin and the centre of the arm, was about 27°c. The maximum tension that the forearm could exert remained steady at reference muscle temperatures of 27°c and above, but at lower reference muscle temperatures the maximum tension that could be exerted was reduced, e.g. to 40 per cent of the original value at a reference muscle temperature of 18°c. Large temperature gradients (of up to 15°c) existed through the muscles from the skin to the centre of the forearm in cool water, so that when the temperature is measured half-way between the skin and the centre of the arm the more superficial fibres may be 5°c (or more) lower than this "reference" temperature.

The evidence suggests that when the reference muscle temperature is lower than 27°c, the reduction in duration of sustained contractions and the fall in maximum tension that can be exerted is due to interference with nervous or neuromuscular transmission to the more superficial (and colder) muscle fibres in the forearm; thus contractions have to be made with less than the total number of existing muscle fibres. At reference muscle temperatures higher than 27°c the fall in duration of sustained contractions is not associated with any reduction in the maximum tension that can be exerted. Blood flows measured through the forearm during and after sustained contractions suggest that with increasing temperature above a reference muscle temperature of 27°c there is an accompanying increase in the rate of metabolism which results in the faster accumulation of a limiting quantity of metabolites to cause fatigue.

(7) "Factors involved in the Causation of Weight Lifting Accidents", by J. R. Brown, Department of Applied Physiology, The London School of Hygiene and Tropical Medicine.

Examination of the statistics provided in the Annual Report of the Chief Inspector of Factories has shown that of the total number of reportable accidents about 30% are due to handling. Although this percentage increased during the war years, it has generally remained constant and has not materially decreased as a result of the introduction of mechanical handling appliances. In 1946 a special investigation was made by the Inspectorate of Factories into the nature and causation of 2,000 handling accidents occurring during the first two weeks of December. It was found that 483 were due to lifting, 328 due to trapping between objects, and 257 due to accidents in connection with trucks, barrows, etc.; the remainder were due to a variety of other causes. These accidents resulted in strains, lacerations, fractures, bruises and abrasions, and involved a great deal of time lost from work.

The indirect factors involved in the causation of weight-lifting (handling) accidents may be divided into :—

General Causes:

Reduction of the working space.
Inadequate dietary intake.
Inadequate or incorrect lighting.
Inadequate ventilation.

Personal Causes:

The accident proneness of the individual.
Numerous psychological disturbances which may arise out of situations in the home and in the workshop.

The commonest direct cause of accidents in work involving lifting is loss of balance with either a heavy or moderately heavy load. A survey by the Factory Inspectorate during February to April 1929 showed that out of 866 cases reported, no less than 146 were due to moving heavy loads and subsequent loss of balance. In this same survey it was shown that muscular strain occurred in 719 and hernia in 128 of the cases reported. The human body has a great capacity for adjusting itself to strain but without the coordination of muscles and organs which follows on good training it will break down. Cathcart has said that the result of training is the capacity to produce the required result with the minimum of effort, or, in more physiological terms, the elimination of incoordinated and useless effort. The work done by the trained man is done with less ultimate fatigue. The avoidance of injury is in some measure due to skill, which is the product of good training and experience ; however, it has been found that men who have been away from their occupation for a long period of time have lost the knack, and injury has been the result.

An appreciable number of handling accidents occur amongst the older age groups and so far as elderly persons are concerned it is necessary to ensure that they are engaged upon work within their physical capabilities. Too often it is not appreciated that although the worker has been doing the same type of work all his life there must come a time when such work is beyond his physical powers. Older men are as vulnerable to strain as are women and young persons, yet as labourers they are often left to carry out the difficult and unpleasant jobs that no one else will perform.

Handling accidents are responsible for a large proportion of the total number of accidents, and the education of all workers both young and old needs much more attention if this type of accident is to be avoided. Instruction must be constant and good teachers are essential ; it should not be left to those who have had but little more training than the trainees themselves. It is in the training of new entrants into industry that the use of a training device such as the Synchrophone is valuable as a means of putting over the basic ideas and right methods and necessary requirements for safety.

(8) " The Incidence and Treatment of Injuries to the Back ", by F. Seager, Medical Officer, Slough Industrial Health Service.

Preliminary notice is given of the Tenth Annual Conference to be held at Balliol College, Oxford, from 6th April to 9th April, 1959, on

ERGONOMICS : ITS PLACE IN INDUSTRY

(Past progress and future trends)

The tenth anniversary of the founding of the Society provides an opportunity to ' take stock ' in view of the growing interest which its activities have aroused both here and overseas, particularly in their applications to industrial work problems.

The broad objectives of the Conference are :—

(*a*) to review the main achievements of ergonomics research and application since the Society was formed ;

(*b*) to present examples of laboratory or field studies which have a direct bearing upon industrial problems ;

(*c*) to discuss future trends, with the needs of industry particularly in mind.

The emphasis will be on the contributions of ergonomics research to industry. There will also be opportunity for critical reappraisal of aims and methods. The Council will invite Speakers to present reviews of past progress and to lead the sessions dealing with future trends.

LIST OF MEMBERS AND THEIR APPOINTMENTS—1958

Addresses are in Great Britain unless otherwise specified

* Denotes a Founder Member.
c Denotes membership of the Council.

Honorary Members

Bartlett, Sir Frederic C., Kt., C.B.E., M.A., Hon. D.Sc., Hon. D.Psy., F.R.S., St. John's College, Cambridge ; Emeritus Professor of Experimental Psychology, University of Cambridge.

c Bedford, Thomas, D.Sc., Ph.D., M.Inst.Min.E., Director, M.R.C. Environmental Hygiene Research Unit, London School of Hygiene and Tropical Medicine, London, W.C.1. (Chairman of Council.)

Burger, G. C. E., M.D., Professor of Occupational Hygiene. Medical Director, N. V. Philips' Gloeilampenfabrieken, Eindhoven, Holland.

Carmichael, Leonard, B.Sc., Ph.D., Secretary, The Smithsonian Institution, Washington, D.C., U.S.A.

Christensen, E. H., Ph.D., M.D., Professor of Physiology and Head of Dept. of Physiology, Gymnastiska Centralinstituet, Stockholm, Sweden.

Clark, Sir Wilfrid Le Gros, Kt., M.A., D.Sc., Hon. D.Sc., F.R.C.S., F.R.S., Professor of Anatomy, University of Oxford.

Evans, Sir Charles Lovatt, Kt., D.Sc., Hon. Ll.D., M.R.C.S., F.R.C.P., F.R.S., Consultant to the Ministry of Supply, C.D.E.E., Porton, Wilts.; Emeritus Professor, of Physiology, University of London.

Hill, A. V., C.H., O.B.E., M.A., Sc.D., Hon. Ll.D., Hon. M.D., Hon. D.Sc., F.R.S., Dept. of Physiology, University College, University of London, formerly Research Professor of the Royal Society.

Ordinary Members

Adam, Major J. M., M.B., Ch.B., B.Sc., R.A.M.C., Physiologist, Medical Research Staff Pool, War Office.

Åkerblom, Bengt, V., M.D., Head Surgeon, The Hospital, Backe, Sweden.

Alloway, D. W. S., Methods Engineer and Training Officer, British Boot, Shoe & Allied Trades Research Association, Kettering.

Annett, J., M.A., Research Worker, Institute of Experimental Psychology, University of Oxford.

Banister, H., B.Sc., M.Sc., Ph.D., Taylor & Francis Ltd., Red Lion Court, London, E.C.4.

Barbour, A. Buchanan, O.B.E., O.St.J., M.R.C.S., L.R.C.P., F.R.Ae.S., Director of Medical Services, British European Airways, Hounslow, Middlesex, Medical Adviser Cyprus Airways, Gibraltar Airways and Alitalia, Medical Consultant to Aer Lingus.

Barcroft, H., M.A., M.D., M.R.C.P., F.R.S., Professor of Physiology, St. Thomas's Hospital Medical School, University of London.

Barlow, W., B.A., B.M., B.Ch., Physician, Dept. of Physical Medicine, Wembley Hospital.

Bastenier, Hervé A. L., M.D., Chargé de Cours, Laboratoire d'Hygiène, University of Brussels, Belgium.

Begbie, G. H., M.A., Ph.D., M.B., Ch.B., Lecturer in Physiology, University of Edinburgh.

Belbin, R. M., M.A., Ph.D., Consultant, " Gaverne ", Old Road, Frinton-on-Sea, Essex.

Belding, H. S., M.A., Ph.D., Professor of Environmental Physiology, Dept. of Occupational Health, University of Pittsburgh, Pa., U.S.A.

Bennett, M. G., M.Sc., F.Inst.P., F.Inst.F., Superintendent, Operational Research Division, Research Dept., British Railways, 20 Euston Square, London, N.W.1.

Bergin, K. G., M.A., M.D., D.P.H., A.F.R.Ae.S., Chief Medical Officer, B.O.A.C., London Airport, Hon. Medical Adviser to the Guild of Air Pilots and Air Navigators and Air League of the British Empire.

Bezemer, F., M.D., Medical Adviser to the Labourinspectorate, Nieuwe Uitleg 12, The Hague, Holland.

Biesheuvel, Simon, M.B.E., M.A., Ph.D., Director, National Institute for Personnel Research, P.O. Box 1176, Johannesburg, S. Africa.

Bink, B., M.D., Physiologist, Dept. of Occupational Medicine, Netherlands Institute for Preventive Medicine, Leyden, Holland.

Body, R. B., M.R.C.S., L.R.C.P., D.I.H., Resident Doctor to the Steel Company of Wales Ltd., Abbey, Margam and Port Talbot.

Bonjer, F. H., M.D., Head of Dept. of Occupational Medicine, Netherlands Institute for Preventive Medicine, Leyden, Holland.

Bouman, M. A., Ph.D., Director, Institute for Perception, R.V.O.-T.N.O., National Council for Applied Research, Soesterburg, Holland.

* Broadbent, D. E., M.A., Director, M.R.C. Applied Psychology Research Unit, Cambridge.

Brooks, C. E., B.Sc., Training Manager, Personnel Administration Ltd., London.

Brough, B. M., B.Sc., Head of the Organisation & Methods Branch, British European Airways, Ruislip, Middlesex.

Brown, J. R., M.B., B.S., B.Sc., Lecturer, Department of Applied Physiology, London School of Hygiene & Tropical Medicine, University of London.

* Browne, R. C., M.A., D.M., M.R.C.P., Nuffield Professor of Industrial Health, University of Durham, King's College, Newcastle-upon-Tyne, 1.

Bruusgaard, A., M.D., Senior Medical Inspector of Factories, Oslo, Norway.

* Burns, W., D.Sc., M.B., Ch.B., Professor of Physiology, University of London, Charing Cross Hospital Medical School, London, W.C.2.

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Chatterjee, S. K., M.B., B.S., D.P.H., D.I.H., Dept. of Applied Physiology, London School of Hygiene & Tropical Medicine, London, W.C.1.

Chennells, Miss Mary H. D., B.Sc., Ph.D., Lecturer in Physiology, Middlesex Hospital Medical School, London, W.1.

Clay, Miss H. M., M.A., Senior Scientific Officer, Dept. of Scientific & Industrial Research, London.

Cleaver, E., Body Experimental Engineer, Austin Motor Co., Ltd., Birmingham.

* Clements, E. M. B., M.B., B.S., Medical Research Council, London.

Connolly, J. V., B.E., F.R.Ae.S., M.I.Prod.E., Director, Sundridge Park Management Centre, Bromley, Kent.

* Conrad, R., M.A., Ph.D., Assistant Director, M.R.C., Applied Psychology Research Unit, Cambridge.

Cook, S. L., B.Sc.(Eng.), Manager, Operational Research Dept., Richard Thomas & Baldwins Ltd., Ebbw Vale, Mon.

Coppock, S. W., M.A., Director of Artillery (Res. & Dev.), Ministry of Supply, London.

Corkindale, K. G. G., B.Sc., Dip.Psych., Psychologist, Institute of Aviation Medicine, Farnborough, Hants.

c Cotes, J. E., M.A., B.M., B.Ch., M.R.C.P., Applied Physiologist, M.R.C. Pneumoconiosis Research Unit, Penarth, Glam.

Courtney-Coffey, G. A., Managing Director, Taylor & Francis, Ltd., Red Lion Court, London, E.C.4.

Cox, David, B.A., Chief Works Study Engineer, Richard Thomas and Baldwins, Ltd., Redbourn Works, Scunthorpe, Lincs.

Cramond, J., M.B., Ch.B., D.P.H., Medical Officer, Imperial Chemical Industries, London.

Crossman, E. R. F. W., M.A., Ph.D., Lecturer in Psychology, University of Reading.

Crowden, G. P., O.B.E., T.D., D.Sc., M.R.C.P., M.R.C.S., Professor of Physiology and Director of Dept. of Applied Physiology, London School of Hygiene & Tropical Medicine, University of London.

* Darcus, H. D., M.A., M.B., B.Sc., Research Officer, R.A.F. Medical Rehabilitation Unit, Chessington, Surrey.

Davies, L. G., Technical Director, Colt Ventilation Ltd., Surbiton, Surrey.

de Jong, J. R., Dr.Tech.Sc., Management Consultant, Hengelo, Holland.

Dilke, N. W., Experimental Officer, National Institute of Agricultural Engineering, Silsoe, Beds.

Draper, John, M.Sc., Statistician, C.S.E.M. of S., Royal Aircraft Establishment, Farnborough, Hants.

Durnin, J. V. G. A., M.A., M.B., Ch.B., Lecturer, Institute of Physiology, University of Glasgow.

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Eckenrode, R. T., B.Chem.Eng., Senior Research Associate, Dunlap & Associates, Stamford, Conn., U.S.A.

*c Edholm, O. G., B.Sc., M.B., B.S., M.R.C.S., L.R.C.P., Head of the Division of Human Physiology, M.R.C. Laboratories, Holly Hill, Hampstead, London, N.W.3. (Hon. Secretary.)

Eklof, Gunnar, Dept. of Furniture and Interior Design, Konsfackskolan, Stockholm, Sweden.

Ellis, Surg.-Cmdr. W. H. B., R.N., A.F.C., M.D., B.S., Farnham, Surrey.

Entwisle, D. G., B.Sc., Research Assistant, Unit for Research on Employment of Older Workers, University of Bristol.

Fitts, Paul M., A.M., Ph.D., Professor of Psychology and Director of the Aviation Psychology Laboratory, Ohio State University, Colombus 10, Ohio, U.S.A.

Fletcher, E., M.A., A.S.A.A., Production Department, T.U.C., London.

Fletcher, John G., M.Sc., Ph.D., F.R.I.C., Division of Human Physiology, M.R.C. Laboratories, Hampstead, London.

* Floyd, W. F., B.Sc., Ph.D., F.Inst.P., A.M.I.E.E., Senior Lecturer in Physiology, Dept. of Physiology, The Middlesex Hospital Medical School, London, W.1., Consultant Physiologist to the British Post Office.

Ford, A. B., M.D., Instructor in Medicine, Western Reserve University, Cleveland, Ohio, U.S.A.

Forrest, D. W., M.A., Ph.D., Lecturer in Psychology, Bedford College, University of London.

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ERGONOMICS

Volume 2 November 1958 Number 1

Contents

Page

Anatomical and Physiological Principles in Chair and Table Design. By W. F. Floyd and D. F. Roberts 1

A Study of Accidents in Relation to Occupation and Age. By Stephen Griew 17

Human Errors and Transport Accidents. By D. Russell Davis 24

Sensori-Motor Performance under Varying Noise Conditions. By John V. Grimaldi 34

The Effects of 'Machine' Lag on a Serial Choice Task with Balanced and Biased Input Frequencies. By J. Alfred Leonard 44

Behaviour in Controlling a Combination of Systems. By K. F. Jackson 52

Warmth and Performance: An Investigation in the Tropics. By R. D. Pepler 63

Effects of Elevated Temperatures on Performance of a Complex Mental Task. By W. Dean Chiles 89

Environmental Conditions and Driving Efficiency: A Review. By K. A. Provins 97

Letters to the Editor 108

Summaries of Papers Published Elsewhere:

(i) Welford, A. T. 110

(ii) Harper, R., McKennel, A. C. and Onions, W. J. 110

(iii) Fleishman, E. A. 111

(iv) Briggs, G. E., Fitts, P. M. and Bahrick, H. P. 112

Obituary Notice: Craig L. Taylor 113

Editorial Note 114

Ergonomics Research Society:

Proceedings 114

Preliminary Notice of 1959 Symposium 118

List of Members 118